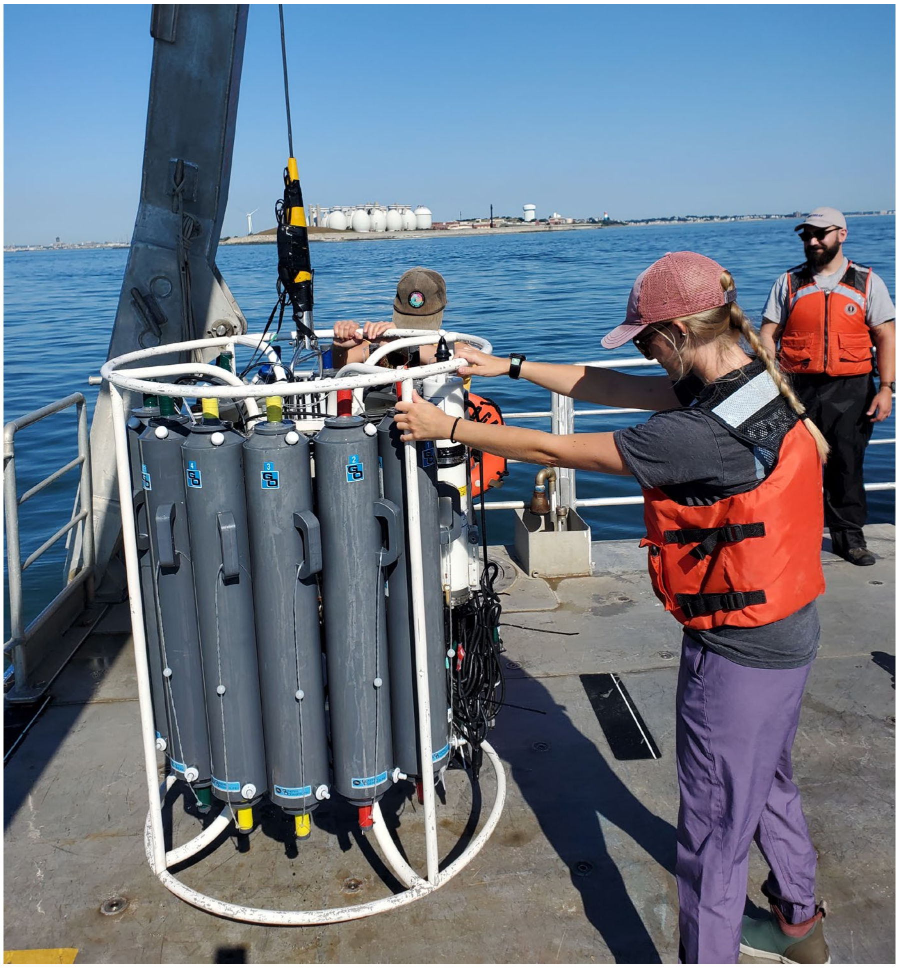
2023 Water Column Monitoring Results



Massachusetts Water Resources Authority
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Report 2024-11

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Cover Photo: CTD-Rosette recovery at station F23 off Deer Island.
Credit: Scott Libby, Battelle on the September 2024 MWRA survey WN248.

2023 Water Column Monitoring Results

Submitted to

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Environmental Quality Report 2024-11

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EXECUTIVE SUMMARY

The Massachusetts Water Resources Authority (MWRA), as part of its National Pollutant Discharge Elimination System (NPDES) permit for the Deer Island Treatment Plant, is required to monitor water quality in Massachusetts and Cape Cod Bays. MWRA implemented a long-term monitoring program to assess the environmental impacts of the MWRA discharge, which in 2000 was diverted from Boston Harbor to Massachusetts Bay. This report documents the results of 2023 water column monitoring, which focuses on water conditions (not sediments, fish, or shellfish) from the ocean surface to the seafloor. The monitoring is intended to evaluate whether the environmental impact of the treated sewage effluent discharged at the MWRA bay outfall meets the expectations of the Supplemental Environmental Impact Statement from the U.S. Environmental Protection Agency (EPA), and whether thresholds of the Contingency Plan[1] attached to the permit have been exceeded. The Contingency Plan thresholds are designed to signal change from baseline conditions before wastewater diversion, not necessarily to indicate environmental degradation.

The major highlight in 2023 was the regional phytoplankton bloom of *Tripos muelleri* during late spring and summer seasons which resulted in extremely low nitrate levels, high chlorophyll and particulate organic carbon concentrations, and low bottom water dissolved oxygen (DO) throughout Massachusetts Bay. The bloom contributed to Contingency Plan water column threshold exceedances for chlorophyll and bottom water DO in 2023 (**Table i**). The 2023 *Tripos muelleri* bloom resulted in high biomass and exceedance of the summer chlorophyll caution level threshold which in turn resulted in an exceedance of the annual caution level. The additional biomass from this bloom also contributed to low DO levels in Massachusetts and Cape Cod Bays and exceedances of caution and warning level thresholds. These DO thresholds were exceeded throughout Massachusetts Bay, both in the 'nearfield' region close to the outfall discharge and at a Stellwagen Basin location far to the north.

Nitrogen, including the dissolved forms nitrate and ammonium, is the most important nutrient for phytoplankton growth in marine waters. Ammonium is the largest fraction of the total nitrogen in wastewater, making it a good effluent tracer. Monitoring in 2023 found elevated ammonium concentrations above baseline conditions frequently within 10 km (6 miles) of the outfall in the direction of prevailing background currents to the south. This is similar to previous years, and consistent with results from water quality models. Other noteworthy observations during 2023:

Physical Conditions

- The most notable physical oceanographic characteristics of 2023 were the warm winter/spring water temperatures, rainy conditions in April leading to early onset of strong seasonal stratification, and low bottom water DO levels.
- Air and surface water temperatures were high compared to historical levels in the winter and close to typical levels for the rest of 2023, with slight cooling in August associated with a cold front and upwelling/mixing, respectively.
- River flow was higher than typical over most of the year, with discharges from the Merrimack River substantially higher than long-term levels in 2023. This contributed to low surface water salinities in April and May and early onset of strong stratification in Massachusetts Bay.

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[1] MWRA's discharge permit includes a Contingency Plan with thresholds that may indicate a need for action if exceeded. The thresholds are based on permit limits, state water quality standards, conditions during the 1992-2000 baseline monitoring period, and expert judgment. "Caution-level" thresholds indicate a need for a closer look at the data to determine the reason for an observed change. "Warning-level" thresholds are a higher level of concern, for which the permit requires a series of steps to evaluate whether adverse effects occurred and, if so, whether they were related to the discharge. If exceedances were related to the discharge, MWRA might need to implement corrective action.

Table i. Contingency Plan threshold values and 2023 results for water-column monitoring. Eight exceedances occurred, with the highest/lowest level of exceedance indicated in red.

Parameter	Time Period	Caution Level	Warning Level	Baseline/ Background	2023
Bottom water DO[a] concentration ($mg\ L^{-1}$)	Survey Mean June-October	<6.5[b]	<6.0[b]	Nearfield[c]: 6.05 SW[d] Basin: 6.23	Nearfield: 5.96 SW Basin: 6.08
Bottom water DO percent saturation (%)	Survey Mean June-October	<80%[b]	<75%[b]	Nearfield: 65.3% SW Basin: 67.2%	Nearfield: 68.0% SW Basin: 62.7%
Bottom water DO rate of decline ($mg\ L^{-1}\ d^{-1}$)	Seasonal June-October	>0.037	>0.049	0.024	0.008
Chlorophyll (nearfield mean, $mg\ m^{-2}$)	Annual	>108	>144	72	116
	Winter/spring	>199	--	50	96
	Summer	>89	--	51	163
	Autumn	>239	--	90	54
Pseudo-nitzschia pungens (nearfield mean, cells L^{-1})	Winter/spring	>17,900	--	6,735	13
	Summer	>43,100	--	14,635	591
	Autumn	>27,500	--	10,500	472
Alexandrium catenella (nearfield, cells L^{-1})	Any nearfield sample	>100	--	Baseline Max 163	32

[a] DO = dissolved oxygen [b] Unless background lower

[c] Stations within about 8 km of the outfall are referred to as "nearfield" and those further away are "farfield"

[d] SW = Stellwagen Basin monitoring station. The deepest monitoring station is located ~16 km (10 mi) NE of the outfall and just outside the boundary of the Stellwagen Bank National Marine Sanctuary.

- The occurrence of lower near-bottom salinity waters has been correlated to higher DO during previous years, but in 2023 this was not the case as bottom water DO levels exceeded Contingency Plan thresholds in the nearfield and Stellwagen Basin in summer and fall 2023 (**Table i**). This indicates that a factor other than physical variability was leading to the steep decline in bottom water DO levels.
- Wind strength and direction followed a typical annual pattern with no particularly large storms or wave events in 2023. Upwelling-favorable winds out of the south were observed in July and August.
- Long-term buoy data show a significant warming of 0.8°C per decade over the duration of the monitoring program and that summertime east-west wind stress is increasingly out of the east rather than the west, which may be contributing to long-term warming.

Nutrients and Phytoplankton Biomass

- Massachusetts Bay seasonal nutrient concentrations were similar to those observed since the outfall was diverted offshore, with some variation. In 2023, concentrations were relatively low in February due to an early winter diatom bloom. Nitrate (NO_3) concentrations declined sharply from March to April and were depleted over the entire water column at Massachusetts Bay stations from May to July due to uptake during the extraordinary *Tripos muelleri* bloom. Silicate levels were high, however, with concentrations exceeding historic maxima during this period due to riverine inputs and lack of utilization by the dinoflagellate, *T. muelleri*. Upwelling/mixing in August and the end of the *Tripos* bloom led to an increase in nitrate in August into the fall.

- As in other years since outfall startup, compared to the baseline years 1992-2000, the 2023 ammonium (NH_4) concentrations during both winter (unstratified) and summer (stratified) conditions were lower in Boston Harbor, higher in the outfall nearfield, intermittently elevated from 10 to 30 km of the outfall, and unchanged further afield. Spatial variability of the effluent plume signal due to prevailing currents was evident with variable and elevated NH_4 observed both within the nearfield and 10-30 km to the south in June, July, and September.
- Chlorophyll concentrations were elevated in February due to a winter diatom bloom. Historically high chlorophyll levels were observed from April to July during the *Tripos muelleri* bloom. Particulate organic carbon (POC) levels were more than double historic maxima during the bloom, as *Tripos* cells are large and have 100-1,000 times more carbon per cell than the more numerous diatoms and microflagellates. Chlorophyll levels decreased sharply from June to July and remained close to long-term means for the rest of the year.
- The *Tripos muelleri* bloom led to nearfield summer chlorophyll levels almost twice the Contingency Plan caution level threshold as well as an exceedance of the annual chlorophyll concentration threshold in 2023 (**Table i**). Both exceedances were driven by high April to June values. This is the first time since the bay outfall began discharging that chlorophyll thresholds were exceeded, showcasing the exceptional nature of this bloom.

Bottom Water Dissolved Oxygen

- Bottom water DO concentrations were low relative to historical data to start the year due to warm water temperatures and decreased quickly with the early onset of strong, seasonal stratification in April and May. June and July levels were well below historical minima at many stations in 2023. The rapid decrease and low bottom water DO levels were likely due to the combination of strong stratification and biological decomposition of senescent *Tripos* biomass. Upwelling or mixing in August led to a leveling off of the decline, but bottom water DO concentrations continued to decline into September and October 2023.
- Lower DO values were also observed at stations in Cape Cod Bay with minima of <4 mg L^{-1} from July to September 2023. Fortunately, unlike 2019 and 2020, there were no observations of hypoxic to anoxic conditions in shallower, nearshore Cape Cod Bay waters.
- DO Contingency Plan thresholds were exceeded in both the Stellwagen Basin and the nearfield in 2023 (**Table i**). Stellwagen Basin bottom water DO percent saturation levels were below the warning level threshold in July and September and DO concentrations were below the caution level threshold in July, September, and October. In the nearfield, the October bottom water DO concentration exceeded the warning level threshold. The bottom water DO depletion rate was only 0.008 mg L^{-1} d^{-1}, which is the lowest rate observed over the monitoring program, but this is because the rate is calculated from June to October and by June 2023 bottom DO levels were already very low.
- Increased water temperatures and stratification resulting from regional changes in long-term summer wind patterns have been identified as a primary factor in the 2019 and 2020 hypoxic DO events in Cape Cod Bay (Scully et al., 2022). These factors continued to play a role in lower DO levels in 2023, but it was the additional biomass from the *Tripos muelleri* bloom supporting increased oxygen consumption that led to the historically low bottom water DO concentrations in June and July 2023.

Phytoplankton and Zooplankton

- The major highlight of 2023 was the extraordinary, monospecific *Tripos muelleri* phytoplankton bloom. The bloom was a regional event, with phytoplankton monitoring programs noting elevated *Tripos* abundance from Maine to Rhode Island during spring/summer 2023. These simultaneous and synchronous patterns suggest that regional drivers (weather, climate, oceanographic variation) are important determinants of phytoplankton patterns.

- *Alexandrium* abundances were very low in Massachusetts Bay in 2023. The highest *Alexandrium* abundance of 32 cells L^{-1} in 2023 was observed in April and was well below the rapid response and contingency thresholds of 100 cells L^{-1}. Paralytic shellfish poisoning (PSP) toxicity was undetectable in Massachusetts coastal waters from the New Hampshire border to Cape Ann and within Massachusetts Bay in 2023. This was also the case throughout the Gulf of Maine (eastern and western) with very low *Alexandrium* abundances and no PSP toxicity except for a few embayments along the eastern side of Cape Cod.
- It is unclear why there was not an *Alexandrium* bloom in 2023 as the abundances in April, though low, were elevated versus historic levels. Physical oceanographic conditions were conducive for dinoflagellates in April and May 2023 with strong stratification which was a factor in the initiation and growth of the *Tripos muelleri* bloom. It may be that the *Tripos* bloom limited *Alexandrium* growth through allelopathic mechanisms or nutrient limitation due to the extremely low NO_3 concentrations.
- 2023 total phytoplankton abundances were mostly at or slightly below long-term mean levels. Total phytoplankton abundance was dominated by elevated microflagellate and dinoflagellate abundance throughout the year, especially the major regional *Tripos muelleri* bloom from April through August. The 2023 total phytoplankton abundance did represent an uptick in the long-term trend, with total phytoplankton abundance recently (2021-2023) trending upward after approximately a decade of declines and low levels.
- Zooplankton taxa, seasonal patterns, and abundances in 2023 were generally similar to those seen in previous years with increases from winter lows through to spring and summer peaks, followed by fall declines.
- Radiolarians, warm-water, oceanic zooplankton, had not been observed prior to 2020 but have now appeared for four years in a row, possibly due to warming waters. The presence of radiolarians aligns with the warmer temperatures recorded for 2023. It may be that Massachusetts Bay is showing signs of warming associated with the northward extension of the Gulf Stream, which has been reported in recent years. This is an important trend to be considered in many Massachusetts Bay monitoring parameters going forward.

LIST OF ACRONYMS

°C	degrees Celsius
µm	micrometer or micron
µM	micromolar concentration
AMP	Ambient Monitoring Plan
ARRS	*Alexandrium* Rapid Response Study
BHWQM	Boston Harbor Water Quality Monitoring
CCS	Center for Coastal Studies
DO	Dissolved oxygen
EM&MS	Environmental Monitoring and Management System
EPA	U.S. Environmental Protection Agency
HAB	harmful algal bloom
km	kilometer
l	liter
m	meter
mg	milligram
MODIS	Moderate-resolution Imaging Spectroradiometer
MWRA	Massachusetts Water Resources Authority
NDBC	National Data Buoy Center Buoy
NERACOOS	Northeastern Regional Association of Coastal and Ocean Observing Systems
NH_4	Ammonium
NO_3	Nitrate
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System
PO_4	Phosphate
POC	Particulate organic carbon
PSP	Paralytic shellfish poisoning
QAPP	Quality Assurance Project Plan
SiO_4	Silicate
WHOI	Woods Hole Oceanographic Institution

1 INTRODUCTION

The Massachusetts Water Resources Authority (MWRA) started monitoring Boston Harbor and Massachusetts and Cape Cod Bays in 1992, to assess baseline conditions before the Deer Island Treatment Plant started discharging treated effluent to Massachusetts Bay in September 2000. Prior to that, sewage was discharged to Boston Harbor, which used to be one of the most polluted urban water bodies in the United States. The objectives of the program are to (1) verify compliance with National Pollutant Discharge Elimination System (NPDES) permit requirements, (2) evaluate whether the environmental impact of the treated sewage effluent discharge in Massachusetts Bay is within the bounds projected by the U.S. Environmental Protection Agency (EPA) Supplemental Environmental Impact Statement (EPA 1988), and (3) determine whether changes within the system exceed thresholds of the Contingency Plan (MWRA 2001) attached to the NPDES permit.

A detailed description of the monitoring and its rationale are provided in the monitoring plans developed for the 'baseline' period prior to relocation of the outfall from Boston Harbor to Massachusetts Bay (MWRA 1991) and for the 'outfall discharge' period since the 2000 relocation (MWRA 1997; and major revisions MWRA 2004, 2010; most recent revision MWRA 2021). For this report, the baseline period with Deer Island and/or Nut Island discharges to the harbor spans from 1992 to September 5, 2000, and the outfall discharge period extends from September 6, 2000 through 2023, when wastewater has been discharged from the bay outfall and not into the harbor. The 2023 data complete 23 years of monitoring since operation of the bay outfall began and 32 years of monitoring since the program began in 1992. **Table 1-1** shows the timeline of major upgrades to the MWRA wastewater treatment system.

Table 1-1. Major upgrades to the MWRA treatment system.

Date	Upgrade
December 1991	Sludge discharges ended
January 1995	New primary plant online
December 1995	Disinfection facilities completed
August 1997	Secondary treatment begins to be phased in
July 1998	Nut Island discharges ceased: south system flows transferred to Deer Island – almost all flows receive secondary treatment
September 6, 2000	New outfall diffuser system online
March 2001	Upgrade from primary to secondary treatment completed
October 2004	Upgrades to secondary facilities (clarifiers, oxygen generation)
April 2005	Biosolids tunnel from Deer Island to Fore River in operation
2005	Improved removal of total suspended solids, etc. due to more stable process
2010	Major repairs and upgrades to primary and secondary clarifiers

Based on the scientific understanding gained since monitoring started in 1992, MWRA's Effluent Outfall Ambient Monitoring Plan (AMP) has been periodically revised to focus on stations potentially affected by the discharge, as well as reference stations elsewhere in Massachusetts Bay (MWRA, 2021). The AMP currently calls for nine one-day water column surveys to be conducted each year (**Table 1-2**). The monitoring surveys were designed to provide a synoptic assessment of water quality conditions. The Center for Coastal Studies (CCS) in Provincetown sampled three Cape Cod Bay stations in the same timeframe, extending the spatial extent of the monitoring. *Alexandrium* abundances were low in 2023 and no additional *Alexandrium* Rapid Response Study (ARRS; Libby et al. 2013) surveys were conducted in 2023. Separately from the AMP, MWRA conducts nutrient, chlorophyll, and bacteria monitoring at several stations in Boston Harbor.

This annual report summarizes the 2023 water column monitoring results, examines conditions over the seasonal cycle during 2023, and compares these conditions with patterns seen during previous years. The water column monitoring is focused on observations potentially attributable to changes to inputs of nutrients and organic matter to the system. The report also tests Contingency Plan Warning and Caution thresholds (**Table i**; MWRA 2001) for bottom water dissolved oxygen (DO) concentrations, percent saturation, and rate of decline; phytoplankton biomass measured as chlorophyll-a; and nuisance phytoplankton species abundance.

Table 1-2. Water column surveys for 2023.

Survey	Massachusetts Bay Survey Dates	Cape Cod Bay Survey Dates	Harbor Monitoring Survey Dates
WN231	February 9	February 9	February 14
WN232	March 21	March 21	March 24
WN233	April 18	April 20	April 13
WN234	May 16	May 15	May 10
WN235	June 21	June 21	June 22
WN236	July 25	July 24	July 20
WN237	August 29	August 28	August 31
WN238	September 12	September 12	
WN239	October 18	October 18	October 25

WN = the nine surveys undertaken each year; only harbor monitoring surveys undertaken within one week of the WN surveys have been included in this report.

1.1 DATA SOURCES

Details of field sampling procedures and equipment, sample handling and custody, sample processing and laboratory analysis, instrument performance specifications, and the program's data quality objectives are given in the Quality Assurance Project Plan (QAPP; Libby et al. 2024). The survey objectives, station locations and tracklines, instrumentation and vessel information, sampling methodologies, and staffing were documented in the survey plan prepared for each survey. A survey report prepared after each survey summarizes the activities accomplished, details any deviations from the methods described in the QAPP, the actual sequence of events, tracklines, the number and types of samples collected, and a preliminary summary of in situ water quality data. The survey report also includes the results of a rapid analysis of >20 micron (µm) phytoplankton species abundance in one sample, the marine mammal observations, and any deviations from the survey plan. Electronically gathered and laboratory-based analytical results are stored in the MWRA Environmental Monitoring and Management System (EMMS) database. The EMMS database undergoes extensive quality assurance and technical reviews. All data for this Water Column Summary Report have been obtained by export from the EMMS database.

1.2 WATER COLUMN MONITORING PROGRAM OVERVIEW

Under the AMP (MWRA 2021) all sampling locations (**Figure 1-1**) are visited during each of the nine planned surveys per year; the 2023 sampling dates are shown in **Table 1-2**. Stations within about 8 kilometers (km) of the outfall are referred to as "nearfield" and those further away are "farfield". Five stations are sampled in the nearfield (N01, N04, N07, N18, and N21), six stations in the Massachusetts Bay farfield (F06, F10, F13, F15, F22, and F23), and three in the Cape Cod Bay farfield (F01, F02, and F29). The 11 stations in Massachusetts Bay (the nearfield and the Massachusetts Bay farfield) are sampled for a comprehensive suite of water quality parameters, including plankton, except N21 which is directly over the outfall. The Massachusetts Bay stations were sampled during one-day surveys; typically, within two days of those dates the three Cape Cod Bay stations were sampled by CCS. All 2023 surveys were conducted within two days of each other in Massachusetts and Cape Cod Bays. Nutrient data from these three Cape Cod Bay stations are included in this report. CCS also has an ongoing water quality monitoring program at eight other stations in Cape Cod Bay, and reports on these separately.[2] MWRA collects samples at 10 stations in Boston Harbor (Boston Harbor Water Quality Monitoring [BHWQM]) at nominally a biweekly frequency.[3] The BHWQM data (nutrient and DO) collected within 7 days (**Table 1-2**) of an AMP survey are included in this report.

In addition to survey data, this report includes Moderate-resolution Imaging Spectroradiometer (MODIS) satellite observations provided by the National Aeronautics and Space Administration, and continuous monitoring data from both the National Oceanic and Atmospheric Administration (NOAA) National Data Buoy Center Buoy (NDBC) 44013 and the Northeastern Regional Association of Coastal and Ocean Observing Systems (NERACOOS) Buoy A01. The satellite imagery provides information on regional-scale patterns, while the buoys sample multiple depths at a single location with high temporal frequency. Buoy 44013 is located ~10 km southeast of the outfall, near station N07; Buoy A01 is in the northwestern corner of Stellwagen Bank National Marine Sanctuary and ~5 km northeast of station F22 (**Figure 1-1**). The time series current observations from Buoy A01 presented and interpreted in the report are the non-tidal currents, isolated from tidal variations by application of a low-pass (33-hour cutoff Butterworth) filter to the raw current data.

The data are grouped by season for calculation of chlorophyll and *Pseudo-nitzschia* Contingency Plan thresholds. Seasons are defined as three four-month periods: winter/spring from January through April, summer from May through August, and fall from September through December. Comparisons of baseline and outfall discharge period data are made for a variety of parameters. The baseline period is February 1992 to September 5, 2000, and the outfall discharge period is September 6, 2000, through December 2023. Year 2000 data are not used for calculating annual means, as the year spans both the baseline and post-discharge periods, but they are included in plots and analyses broken out by survey and season.

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[2] CCS station map and data available at http://www.capecodbay-monitor.org/

[3] BHWQM station map ("nutrient monitoring") at http://www.mwra.com/harbor/graphic/harbor_sampling_locations_detail.jpg

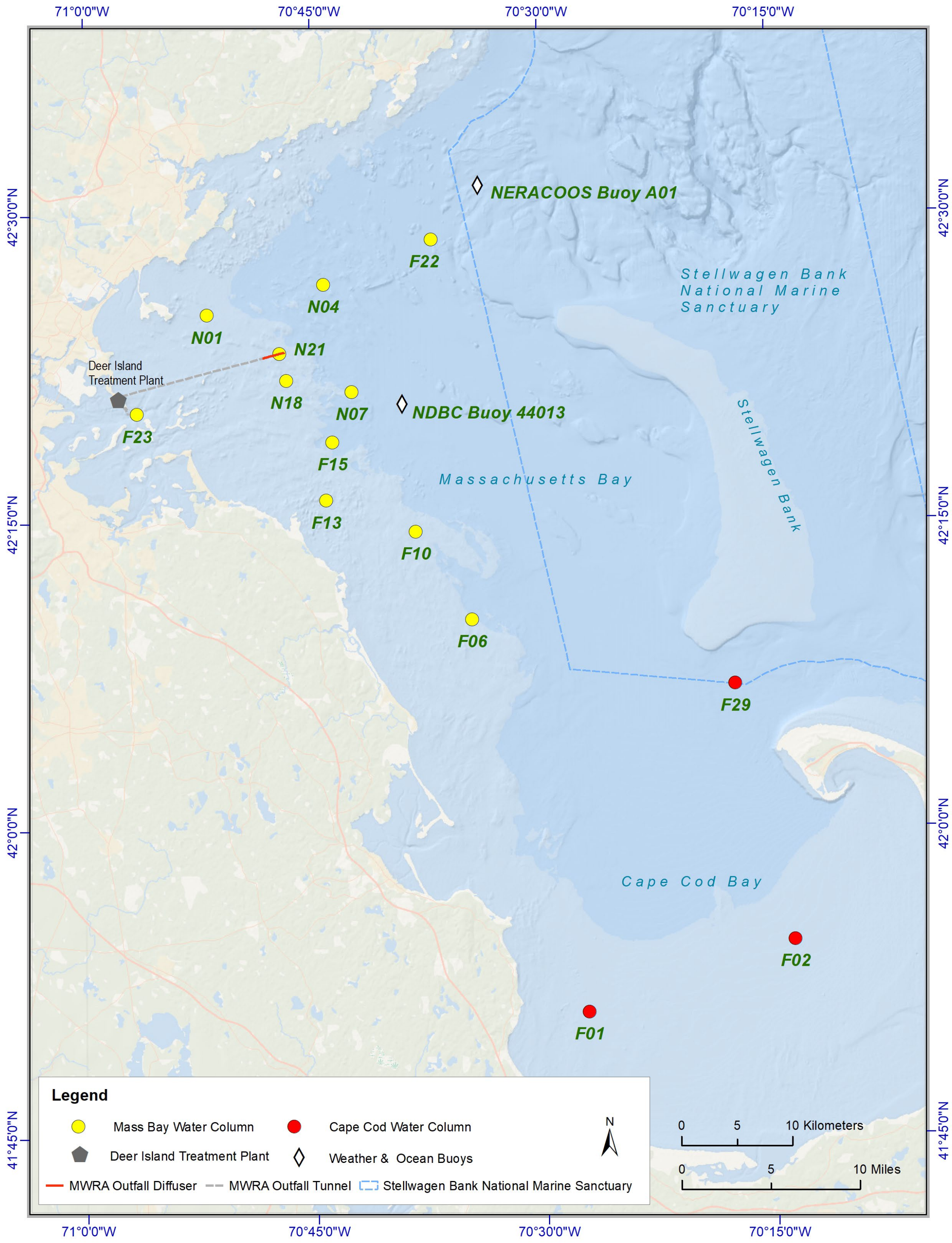


Figure 1-1. **Water column monitoring locations.**

2 2023 MONITORING RESULTS

2.1 BACKGROUND

The Massachusetts Bay ecosystem exhibits a seasonal cycle during which its physical structure, biology, and biogeochemical cycling change. External processes (meteorological and river forcing, exchange with offshore waters) and ecological changes influence the seasonal pattern. Each year specific details of the cycle can differ spatially across the bay system and temporally due to interannual variability.

During winter, when the water column is vertically well mixed and light intensities are low, nutrient concentrations in the bay are typically relatively high and amounts of phytoplankton are typically moderate to low. Zooplankton counts are also typically low over the winter. During most, but not all years, as light intensities and temperatures increase in late winter, phytoplankton growth increases and develops into a winter/spring bloom. This bloom typically occurs in March or April, but the intensity of the bloom can vary greatly, as can its timing. Diatoms (e.g., *Chaetoceros*, *Skeletonema*) are usually responsible for the winter/spring bloom, and in certain years, these blooms are followed by blooms of the prymnesiophyte *Phaeocystis pouchetii*. During May through June of certain years, *Alexandrium catenella*, the organism responsible for paralytic shellfish poisoning (PSP), is transported from the north into the bay. The extent to which *Alexandrium* are transported into the bay varies greatly between years due to variability in the occurrence of the offshore populations and in the oceanographic currents needed to bring them into the bay.

During the transition into summer, the water column becomes stratified, nutrient concentrations in the surface waters are depleted by phytoplankton consumption, and phytoplankton biomass typically declines. Phytoplankton biomass during this season often has a characteristic vertical structure with mid-depth maximum at or near the pycnocline about 15 to 25 meters (m) deep, where cells have access to both adequate light and nutrients; DO concentrations have similar mid-depth maximum, as influenced by phytoplankton production.

During summer, zooplankton abundance in the bay is typically relatively high, but the size and nature of the zooplankton communities can vary widely year to year. *Oithona similis*, *Pseudocalanus* spp. and *Calanus finmarchicus* are often the most abundant zooplankton taxa during summer. However, episodic spawning events can lead to large spikes in the abundance of meroplankton (e.g., bivalve veligers, barnacle nauplii), which dominate total zooplankton when they occur.

During summer, when water temperatures are high and the water column is stratified, bottom water DO concentrations, which are typically relatively high year-round, decline. Vertical mixing of the water column in the fall, often facilitated by storms, re-aerates the water column. The extent to which bottom water DO concentrations decline during the summer into fall, and the date in fall when they begin to increase can also vary widely from year to year.

In the fall, the water column de-stratifies as incident irradiance intensities decline, water temperatures decrease, and vertical mixing increases due to more intense winds. This returns nutrients to surface waters and leads to increases in phytoplankton populations. The magnitude and timing of these fall blooms can vary widely year to year. Taxa responsible for the fall blooms typically include *Skeletonema* spp. and *Dactyliosolen fragilissimus*.

This general sequence has been evident every year of this 32-year dataset (1992-2023). The major features and differences observed in 2023 are described below. The highlight in 2023 was the major regional phytoplankton bloom of *Tripos muelleri* which resulted in extremely low nitrate levels, high chlorophyll and particulate organic carbon (POC) concentrations, and low bottom water DO throughout Massachusetts Bay.

2.2 PHYSICAL CONDITIONS

To provide an overview of physical conditions in Massachusetts Bay in 2023, conditions at stations N18 and F22 are described. These are representative of the nearfield and waters entering Massachusetts Bay from the north, respectively. Surface water temperatures were warm compared to historical levels at station N18 from February to July before decreasing below the long-term mean in August due to upwelling (**Figure 2-1**). Surface water temperatures again increased to historic maxima by early September and remained warm into October. This trend was observed across the bays as similarly high temperatures were seen at station F22 farther offshore from February to July, decreasing to historic median levels in August before increasing to maximum levels in September and October (**Figure 2-2**). Bottom water temperatures were consistently in the upper quartile at both stations N18 and F22 from February to October, even reaching above historical maxima at station N18 in July and October. Air temperatures were unusually warm during the winter and fall but were close to average for the rest of 2023 at NERACOOS buoy A01. Near-surface water temperature at the NDBC buoy was consistent with the data from station N18 with unusually warm wintertime temperatures, and normal temperatures for the rest of the year, with the exception of abrupt cooling in August, due to cold fronts and upwelling (**Figure 2-3**).

Surface salinity was near the long-term median in February and March at both stations N18 and F22. There was a sharp decline in surface salinity to historic minimum at station F22 in April and continuing into May (**Figure 2-2**). This coincided with peak spring Merrimack River flows (**Figure 2-4)**. The decrease in surface water salinity was observed in May at station N18; the delay was likely due to transport time associated with circulation of the fresher waters into the bay (**Figure 2-1**). River flows were near 32-year maxima over the summer and remained elevated for the rest of 2023. The elevated flow and associated precipitation contributed to surface salinity levels well below the long-term median and often at historic minima from May to October 2023. Bottom water salinity was close to the long-term median for most of 2023 with slightly lower salinities observed in the nearfield in June and October.

The low salinity surface waters in April and May 2023 resulted in early and strong stratification in Massachusetts Bay. Stratification, presented as the difference in density between near-surface and near-bottom waters, was close to the long-term median in February and March, increased sharply in April, and reached long-term maxima at most stations in May 2023 (**Figure 2-5**). The April and May changes were especially evident at offshore stations F22 and N04 due to the high river flow with lower surface salinity in April and May. By June, stratification had decreased closer to the historic median across the bay (except station F22) coinciding with increased surface water salinity and commensurate with an increase in bottom water temperature (**Figure 2-1**). Annual maxima in stratification observed in July were well above historic July maxima at many stations. Stratification decreased in August in association with the upwelling favorable conditions and cooling of the surface waters. In September, stratification increased to historical maxima again and although levels dropped sharply by October, stratification remained close to historical maxima due to the lack of major storms in the fall of 2023. The persistence of stratified conditions from April into late October was one of the factors in the low bottom water DO levels observed in 2023. The impact of stratification on bottom water DO concentrations is described in more detail in Section 2.4.

Wind speeds and directions were typical for all of 2023, with no particularly large storms or large wave events. The upwelling index is the monthly average of the north-south component of wind stress (**Figure 2-6**). A positive index indicates more wind from the south, which favors upwelling and cooling of both surface and bottom waters. The index showed no net upwelling in June and strong upwelling in July and August. The impact of the summer cold fronts and upwelling favorable winds was evident in cooling surface waters at the NDBC buoy in August (**Figure 2-3**). This upwelling may have contributed to the mitigation of the drop in DO that was occurring in the spring and early summer. The index decreased sharply to strong downwelling in September and then weak downwelling through the remainder of the year.

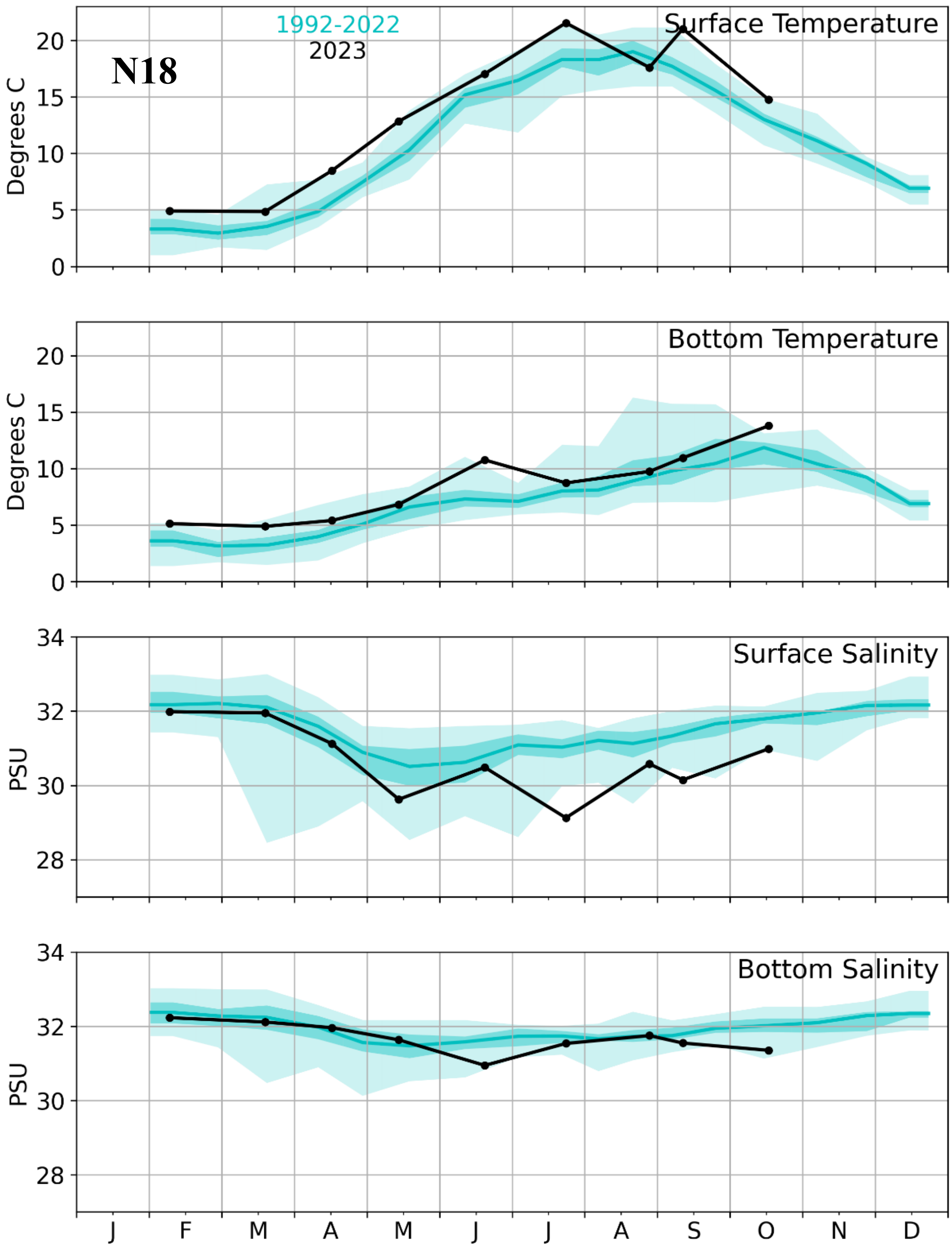


Figure 2-1. Comparison of 2023 surface and near bottom water temperature (°C) and salinity (PSU) at nearfield station N18 relative to prior years. 2023 results are in black. Results from 1992–2022 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

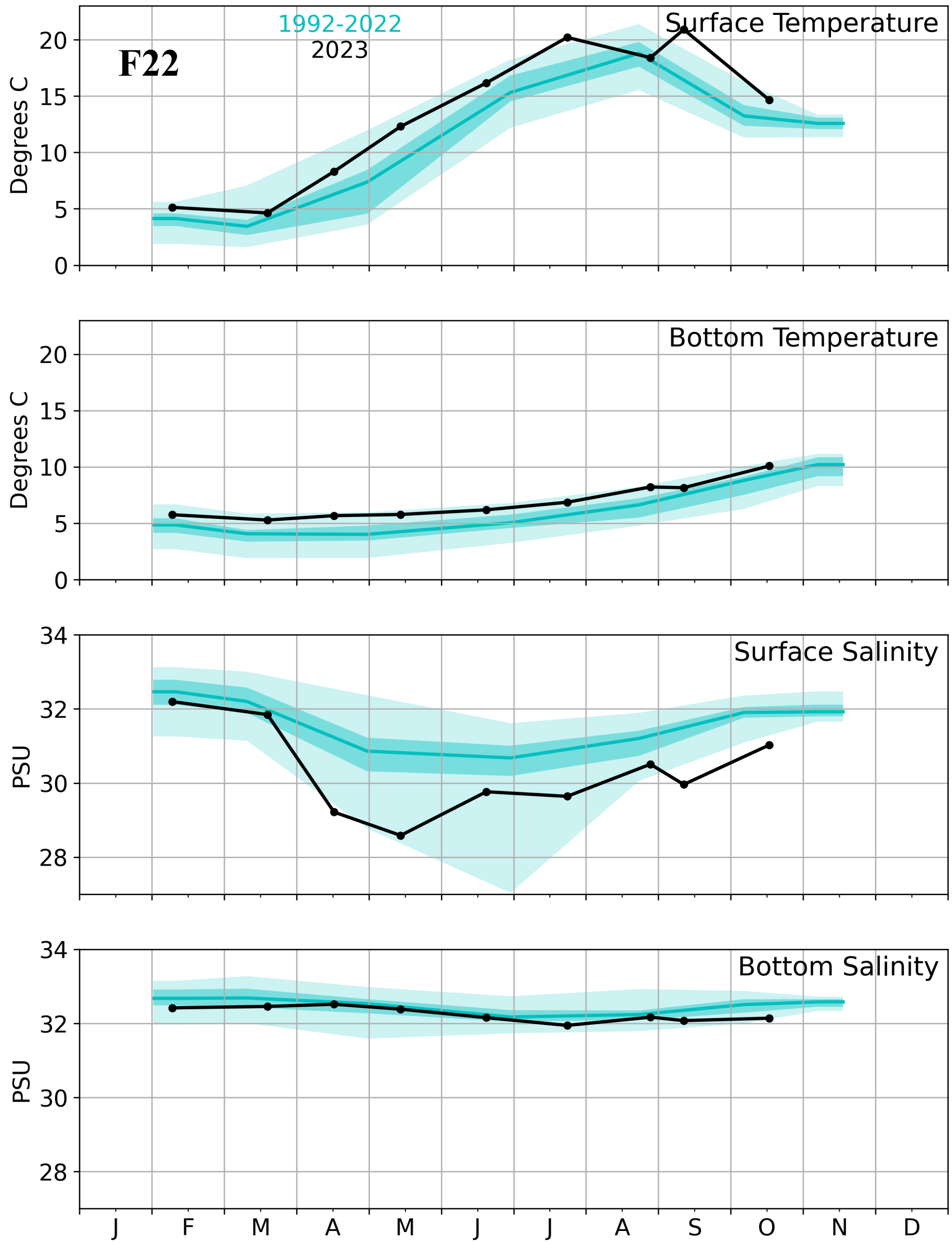


Figure 2-2. Comparison of 2023 surface and near bottom water temperature (°C) and salinity (PSU) at farfield station F22 relative to prior years. 2023 results are in black. Results from 1992–2022 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

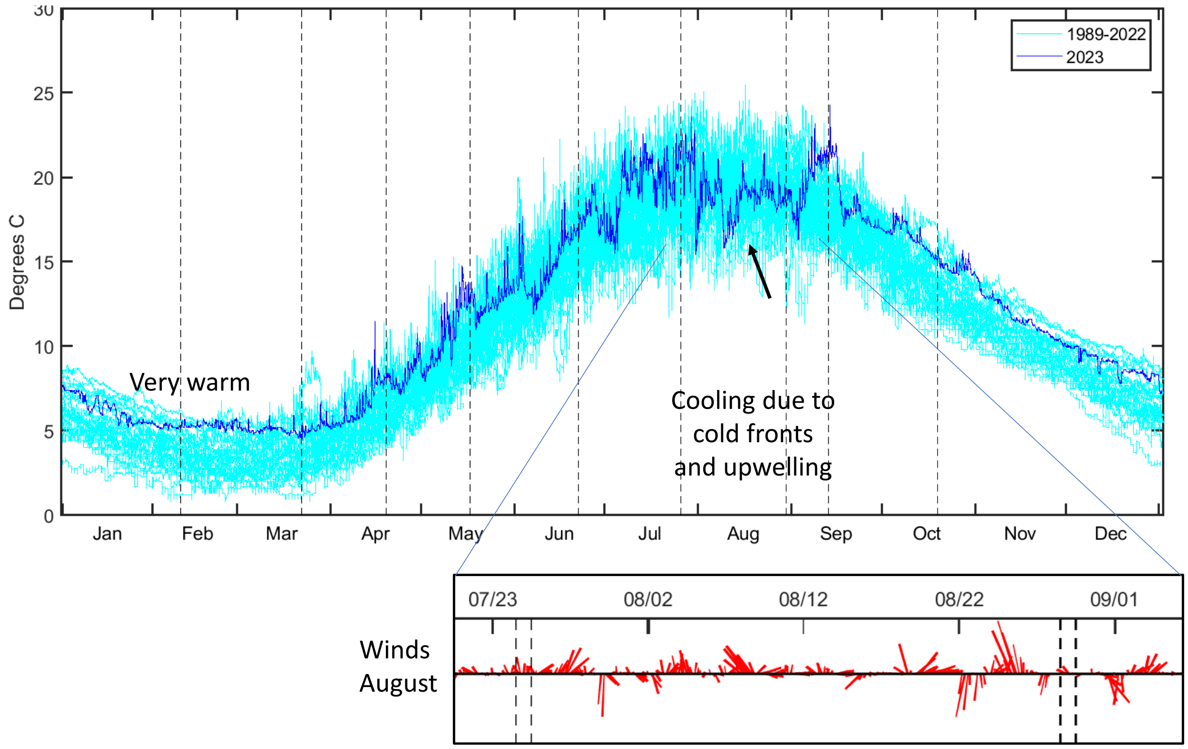


Figure 2-3. NDBC Buoy 44013 time series observations of near-surface temperature (°C, top) and surface wind stress (Pa) and direction (bottom) in 2023. The red lines represent wind flow in the direction away from the origin line; northward up and eastward to the right. Vertical dotted lines represent survey dates.

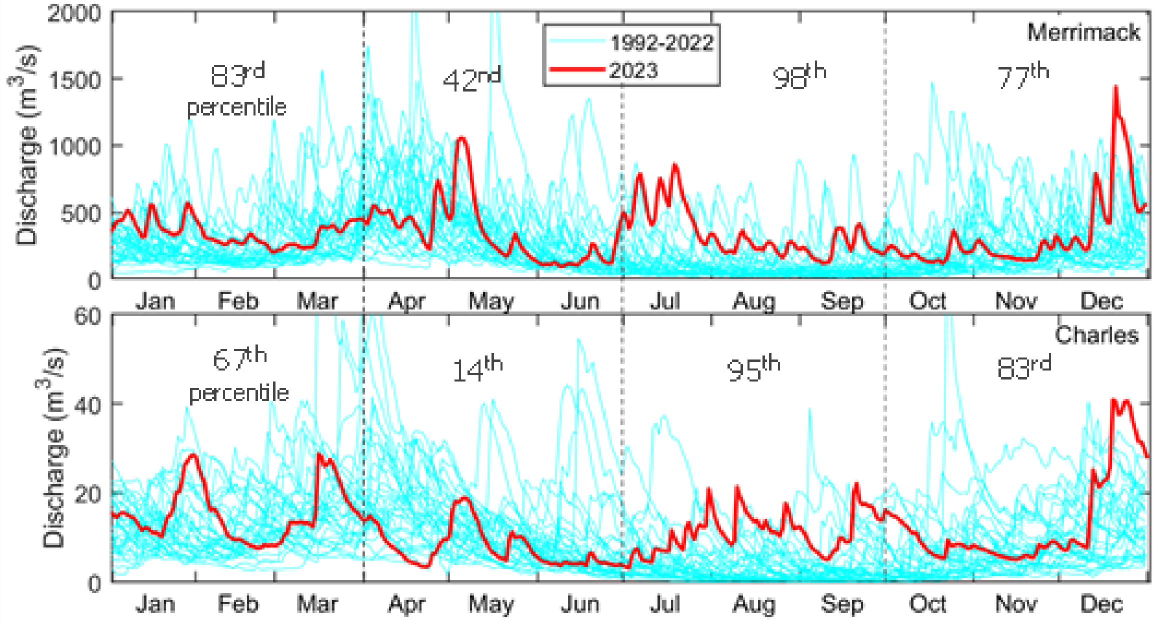


Figure 2-4. Comparison of 2023 river discharge (m^3/s) for the Merrimack (top) and Charles (bottom) Rivers (solid red line) with 1992-2022 (light blue lines). The percentiles represent 2023 flow, compared to the entire 32-year record, during each quarter of the year.

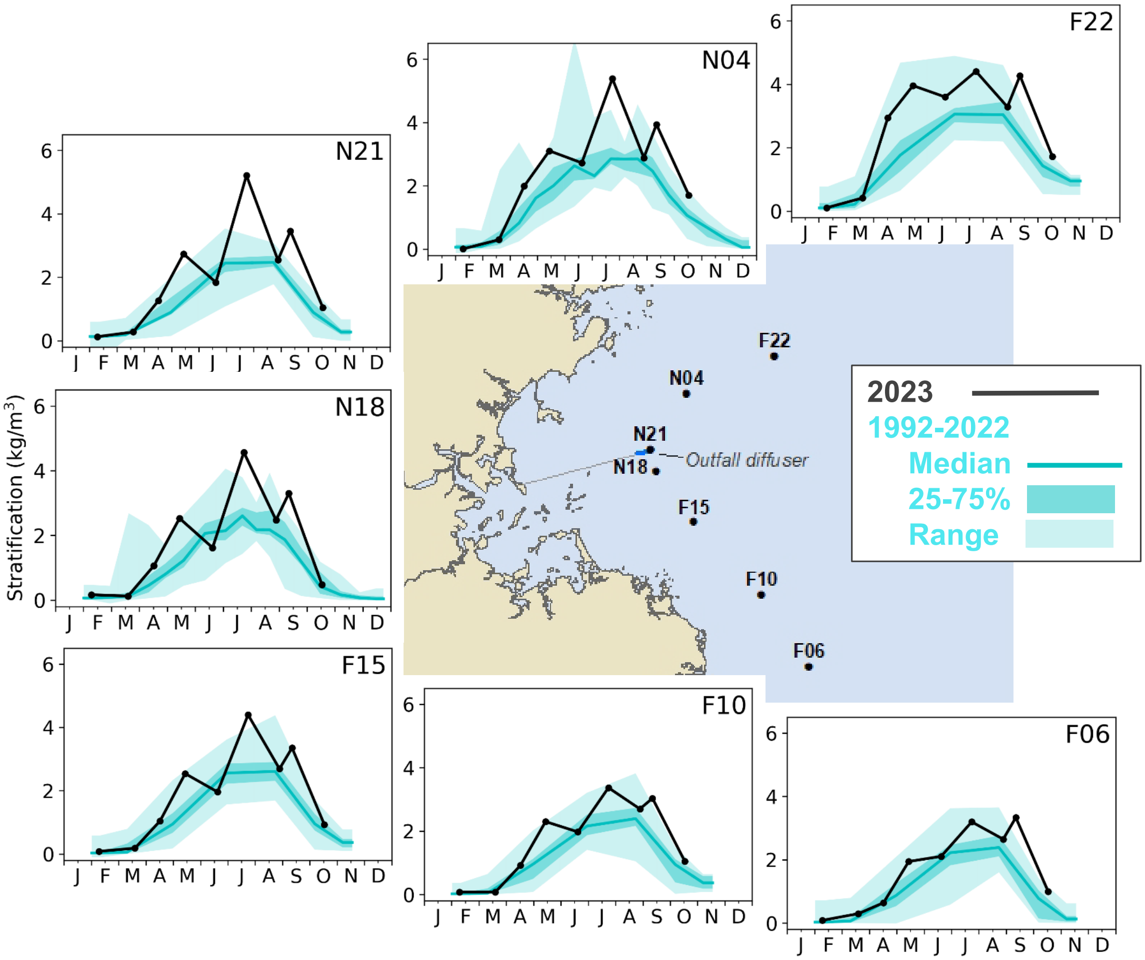


Figure 2-5. Stratification (Δ sigma-t; kg m^{-3}) at selected stations in Massachusetts Bay for 2023 compared to prior years. 2023 results are in black. Results from 1992–2022 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

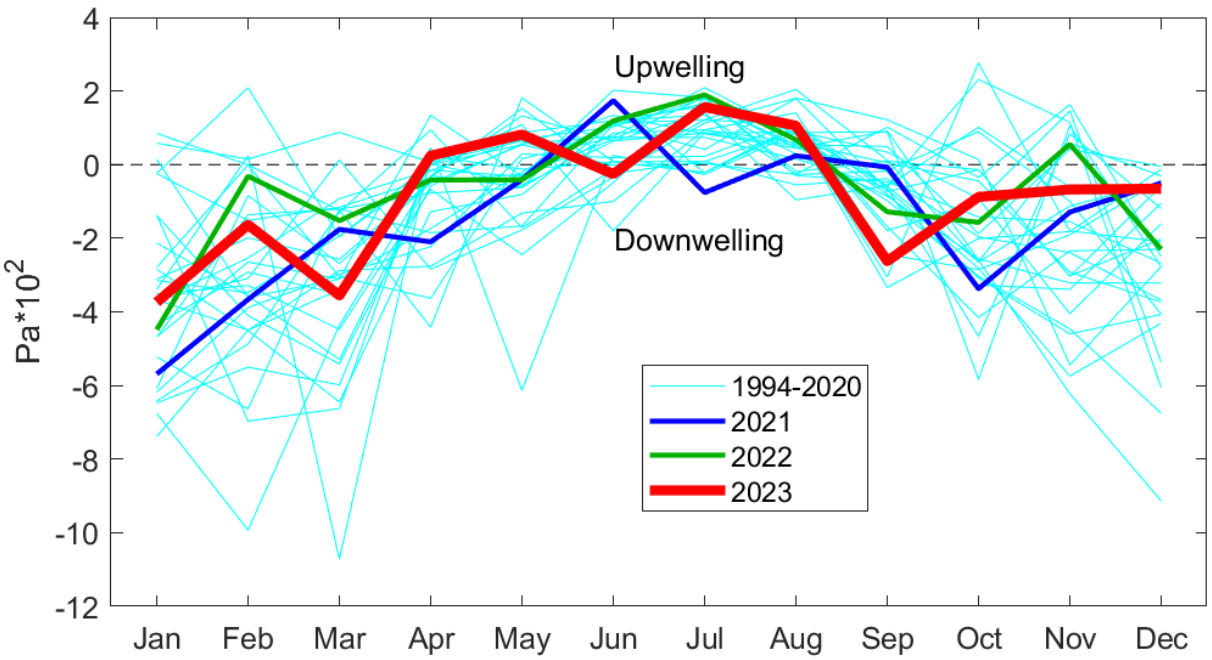


Figure 2-6. Upwelling index (100 x Northward component of wind stress; Pascals) at NOAA Buoy 44013. 2023 results are in red, 2022 in green and 2021 in blue. Results from 1994–2020 in cyan. Positive values indicate winds from the south, which result in upwelling-favorable conditions; negative values indicate winds from the north, which favor downwelling.

The long-term time series of summertime air and water temperature based on the NOAA buoy shows surface waters warming more rapidly than air temperatures (nearly 1 degree Celsius [°C] per decade; **Figure 2-7** top). This warming may be influencing changes in the species distribution and abundance in Massachusetts Bay. A review of the long-term wind data indicates that the north-south wind stress has no discernable trend during July-August, whereas the east-west wind stress shows an increase in the incidence of summertime Easterlies (**Figure 2-7** bottom). This trend may be influencing long-term warming, based on preliminary modeling by Malcolm Scully at Woods Hole Oceanographic Institution (WHOI; Scully et al. 2022).

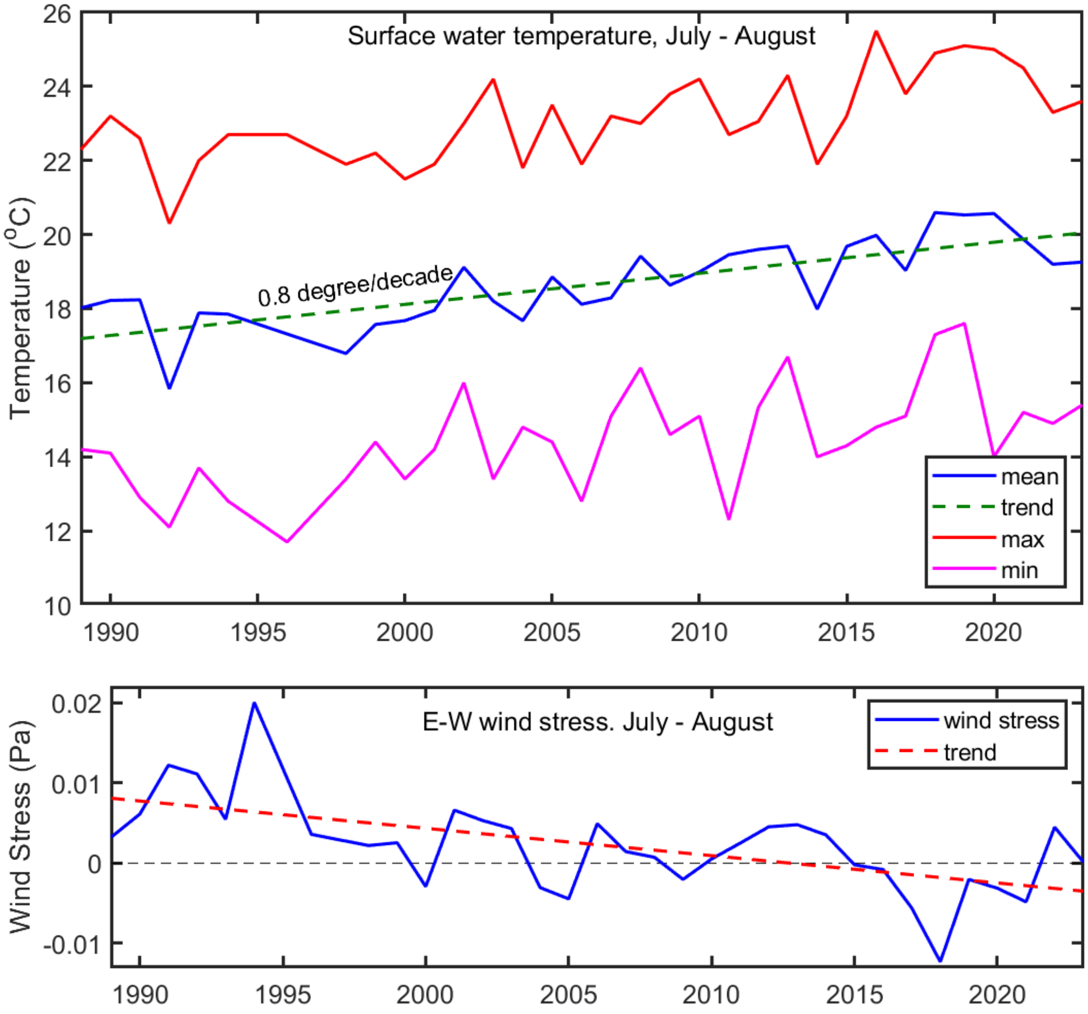


Figure 2-7. Comparison of average July-August surface water temperature (°C, top) and east-west wind stress (Pa) at Buoy 44013 in Massachusetts Bay from 1992-2023.

2.3 NUTRIENTS AND PHYTOPLANKTON BIOMASS

This section documents dissolved inorganic nutrient concentrations and phytoplankton biomass in the bay during 2023. It also quantifies the spatial extent of the outfall's nutrient and chlorophyll biomass signals.

2.3.1 Nutrients

During most years, over much of Massachusetts and Cape Cod Bays, concentrations of the dissolved inorganic nutrients nitrate (NO_3), silicate (SiO_4) and phosphate (PO_4) reflect the seasonal cycles of nutrient inputs from rivers and the Gulf of Maine, and phytoplankton uptake. Depth-averaged concentrations tend to be elevated from February into April, relatively low from May into August or September, and then increase into October and the winter. At station N18, located in the nearfield and 1 km south of the outfall, NO_3, SiO_4 and PO_4 all showed this basic seasonal pattern in 2023 with some interesting departures from the trends which are discussed below (**Figure 2-8**). Ammonium (NH_4) (**Figure 2-8**, upper right) does not exhibit this seasonal pattern in the bay, and was quite variable in 2023 alternating between high and low levels over the course of the year (**Figure 2-8**, upper right).

Nutrient concentrations were close to long-term medians in February and March 2023. Nitrate concentrations were slightly above the historic median, SiO_4 levels were slightly below the median in February and increased into March, while NH_4 and PO_4 concentrations at station N18 were in the upper quartile (**Figure 2-8**). The relatively low SiO_4 concentrations in February suggest there may have been a diatom bloom prior to the February survey.

From March to April 2023, there was a sharp decline in NO_3 concentrations at station N18 and throughout Massachusetts Bay from levels in the upper quartile in March to the lower quartile of long-term levels at most stations in April (**Figure 2-9**). At deeper offshore stations, NO_3 was nearly depleted over the water column and station average concentrations reached historic minima. There was a coincident decrease in SiO_4 levels from March to April. This decrease in both nutrients suggests there was likely an increase in diatoms, but the primary reason for the exceptionally low NO_3 concentrations was the initiation of the *Tripos muelleri* bloom.

Nitrate concentrations remained very low from April through July with levels depleted at many stations in May, June, and July (**Figure 2-9**). Silicate levels, however, were high from May to July with concentrations exceeding historic maxima at most stations during this period (**Figure 2-8**). The low NO_3 was due to its utilization by the extraordinary regional *Tripos* bloom, while the high SiO_4 concentrations resulted from riverine inputs and lack of utilization by the dinoflagellate, *T. muelleri*. This bloom resulted in remarkably high chlorophyll and POC levels in April (see **Figure 2-14** and **Figure 2-15**).

Survey mean NO_3 levels increased slightly from June to July at nearshore stations and even more from July to August after the *Tripos* bloom ended (**Figure 2-9**). July and August were a period of upwelling favorable winds (**Figure 2-6**) which mixed the water column, bringing deeper nutrient-rich bottom water inshore and to shallower depths. From August to October, NO_3 concentrations remained close to the long-term median at most stations. Overall, there was considerable variability in NH_4 and PO_4 levels, which both peaked at station N18 in February and September 2023 (**Figure 2-8**). Ammonium concentrations have been more variable over the course of the summer in the nearfield since the bay outfall came online in 2000, as expected (**Figure 2-10**).

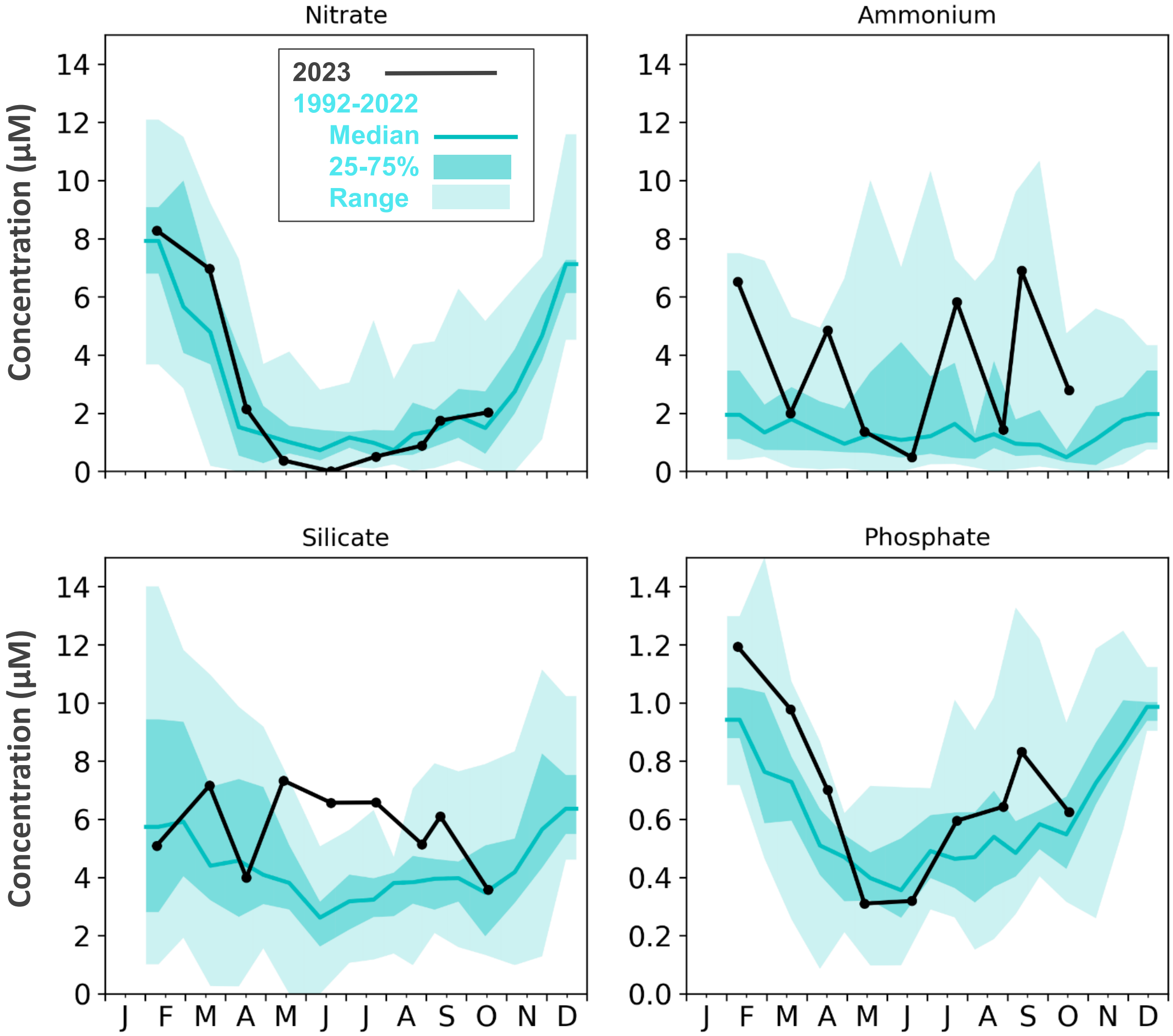


Figure 2-8. Depth-averaged dissolved inorganic nutrient concentrations (µM) at station N18, one kilometer south of the outfall, in 2023 compared to prior years. Note difference in y-axis scale for phosphate. 2023 results are in black. Results from 1992–2022 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

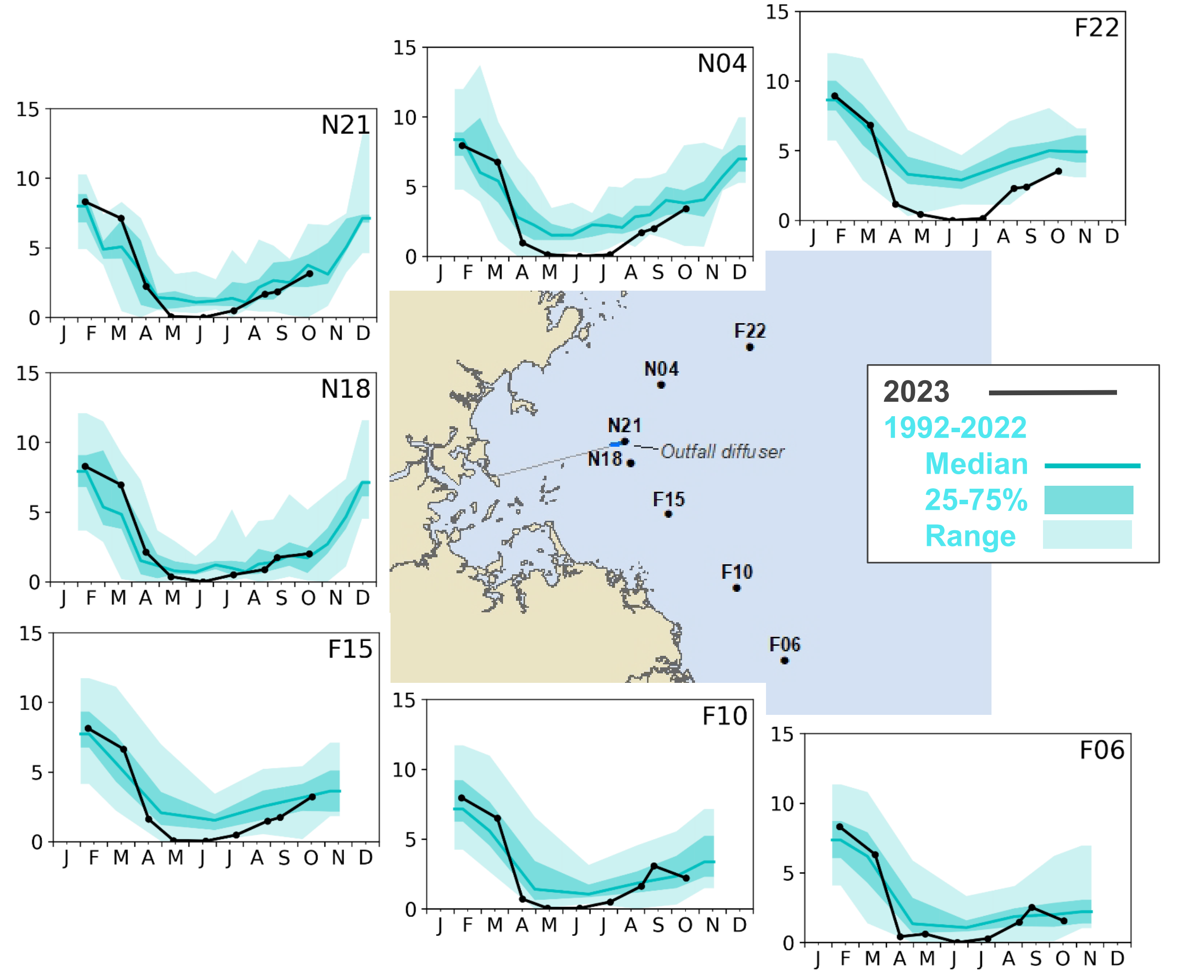


Figure 2-9. Depth-averaged nitrate (µM) at selected stations in Massachusetts Bay for 2023 compared to prior years. 2023 results are in black. Results from 1992–2022 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

As typically observed, the bay outfall effluent plume was characterized by elevated NH_4 concentrations in the nearfield during most of the surveys in 2023 (**Figure 2-10**). The plume signature of elevated NH_4 concentrations was seen within 10 to 20 km of the bay outfall during both well-mixed and stratified conditions (**Figure 2-11**). However, elevated NH_4 concentrations observed in June and July 2023 may also be due to senescence and degradation of the *Tripos* bloom. The dramatic changes in NH_4 concentrations in Boston Harbor and the nearfield are highlighted by comparing data from pre- and post-diversion periods (**Figure 2-10**). NH_4 concentrations have decreased dramatically in the harbor, while in the nearfield levels near the outfall at stations N18 and N21 have shown a substantial increase as expected and are usually variable from survey to survey. In 2023, this is highlighted with NH_4 concentrations in the upper quartile or higher at station N18 in February, April, July, and September and at station N21 in March and June with low concentrations seen during other months at both stations. Such large differences in NH_4 concentrations between these two stations and the survey to survey variability observed is due to sampling within or outside of the effluent plume and its associated mixing zone.

As can be seen in **Figure 2-10**, increases in NH_4 above background conditions were observed in April, June, and July 2023 about 10 km from the outfall in the direction of prevailing background currents to the south. This is similar to other years since the bay outfall became operational in late 2000. In February, when the water column was vertically well mixed, the NH_4 plume signature was most pronounced in the nearfield surface waters and at stations N21 and N18 (**Figure 2-11**). When the water column becomes stratified, high NH_4 concentrations (>8 µM) were observed at or below the pycnocline at nearfield stations N21 and N18. In June, elevated NH_4 concentrations >4 µM were also observed in the bottom waters at stations 10 to 20 km south of the outfall.

The trend in NH_4 and NO_3 from April to July 2023 during the *Tripos* bloom is highlighted by looking at a north to south transect across Massachusetts Bay (**Figure 2-12** and **Figure 2-13**). In April, at the start of the *Tripos* bloom, chlorophyll fluorescence was elevated along the transect, while both NH_4 and NO_3 were low in the surface waters but present in elevated concentrations below the pycnocline likely supporting the bloom. *Tripos* is a dinoflagellate that can vertically migrate to utilize nutrients at depth and move into the upper water column and higher irradiances to photosynthesize. By May and June, NO_3 was depleted over all depths and chlorophyll fluorescence was high over most of the water column. Elevated NH_4 concentrations were primarily restricted to the effluent plume below the pycnocline near the outfall and 10 km to the south at station F15 from June to July. In July, NO_3 remained very low over the entire transect, chlorophyll fluorescence levels decreased, and NH_4 concentrations appeared to have increased. The higher NH_4 levels were likely due to a combination of both the effluent plume and degradation of the *Tripos* bloom as the cells died off and decomposed below the pycnocline.

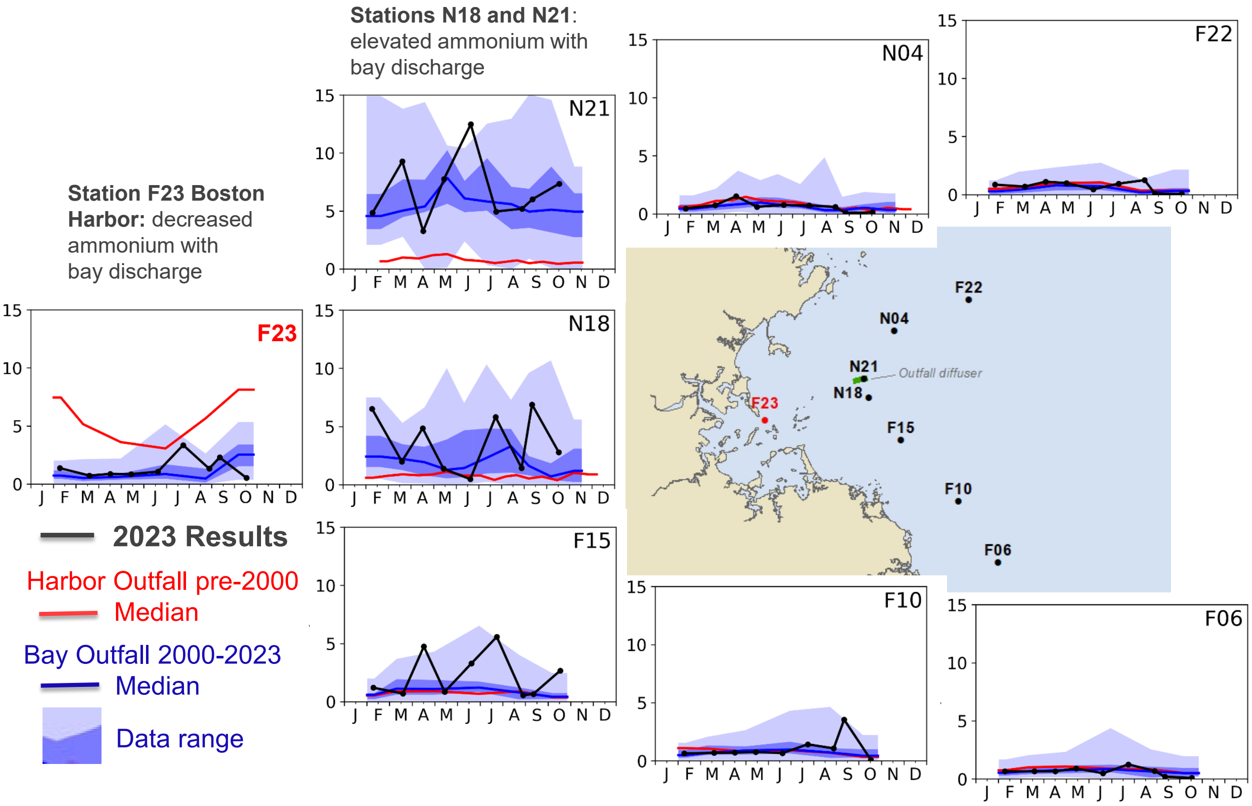


Figure 2-10. Depth-averaged ammonium (NH_4) (µM) at selected stations in Massachusetts Bay for 2023 compared to prior years. 2023 results are in black; baseline (1992-August 2000) results are in red; and post-diversion (September 2000-2022) results are in blue. For baseline and post-diversion: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range.

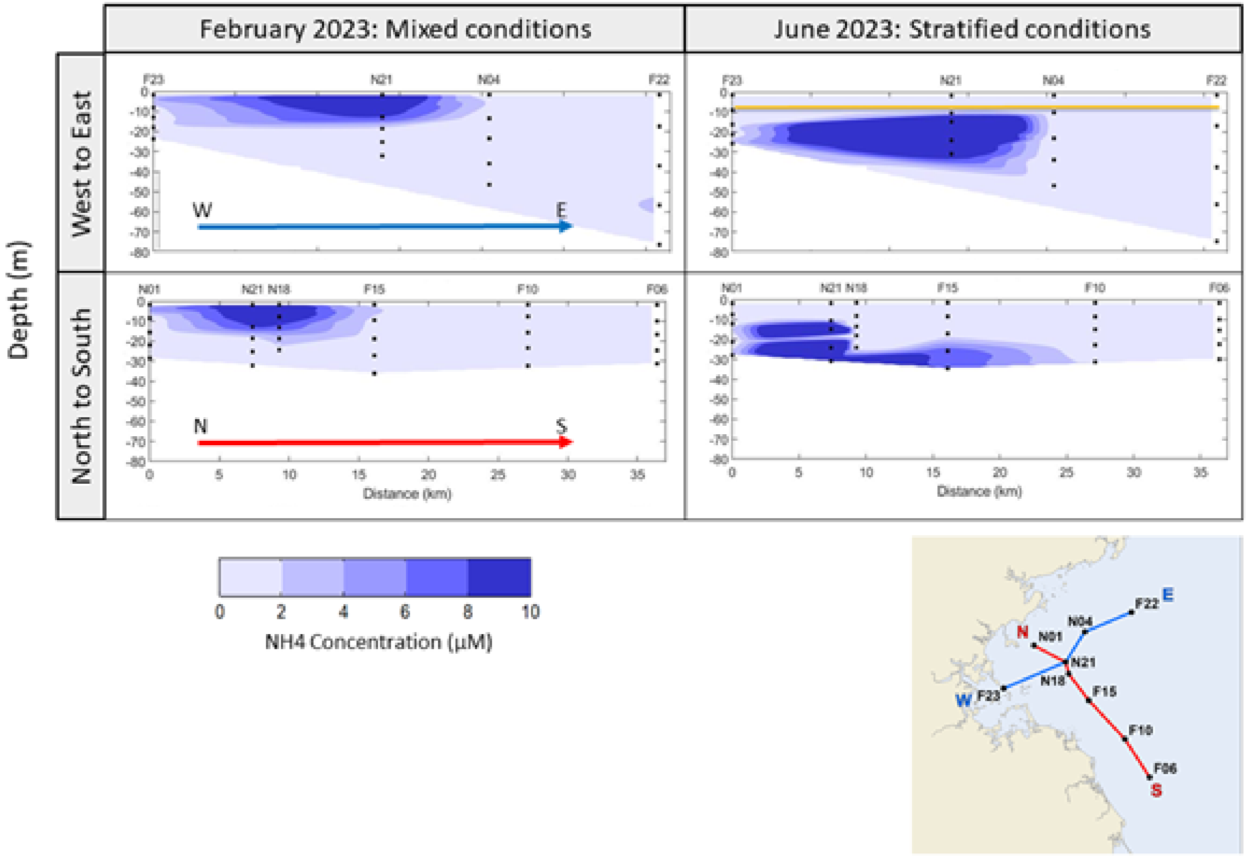


Figure 2-11. **Cross-sections of water column NH_4 concentrations along transects connecting selected stations.** Pycnocline shown as yellow line in June 2024 under stratified conditions. Small black dots in the plots at right indicate the sampling depths for nutrients. Transects shown in map**.**

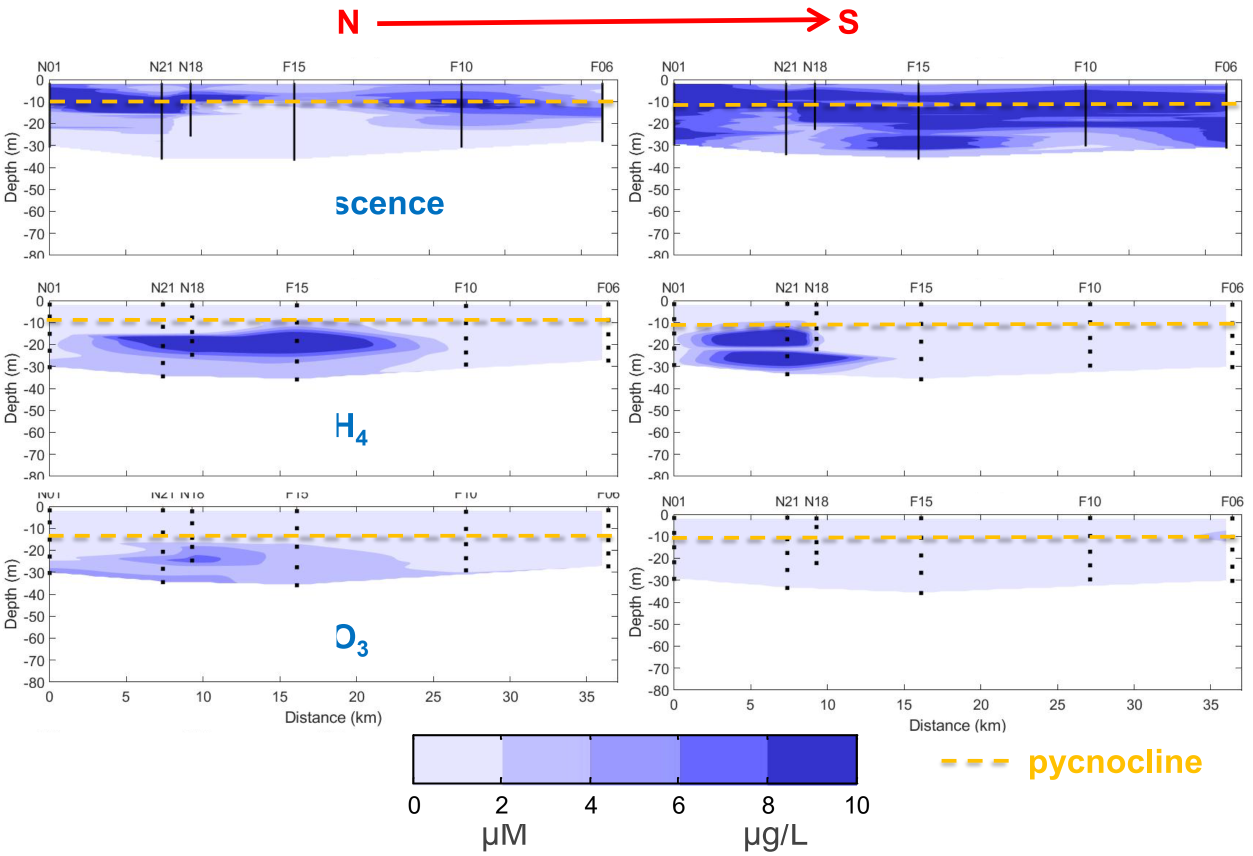


Figure 2-12. Chlorophyll from fluorescence (top; µg L^{-1}), ammonium (middle; µM), and nitrate (bottom; µM) during the April (left) and May (right) 2023 surveys along the north-south transects shown in Figure 2-11. Dots (nutrients) and lines (fluorescence) indicate the sampling depths and downcast profile in situ depths. The yellow line indicates the approximate depth of the pycnocline.

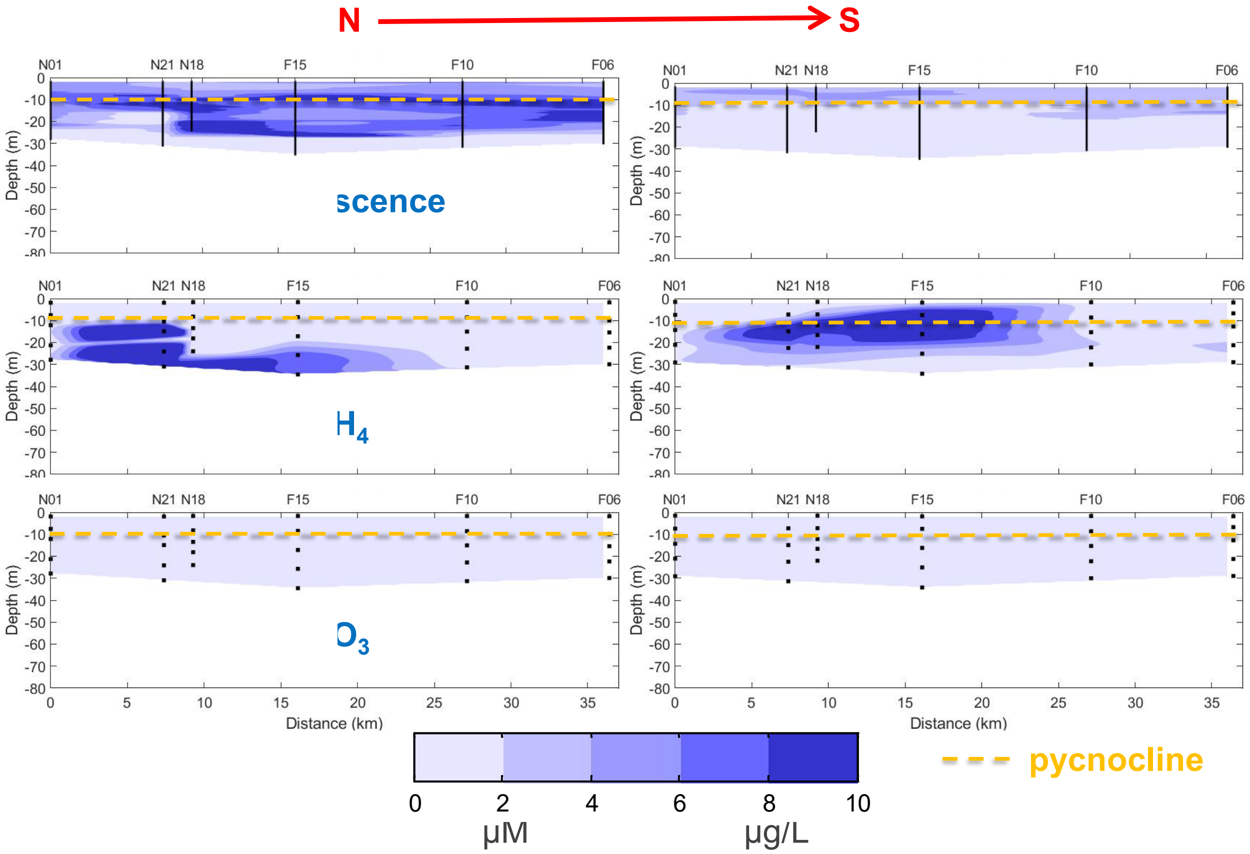


Figure 2-13. Chlorophyll from fluorescence (top; µg L^{-1}), ammonium (middle; µM), and nitrate (bottom; µM) during the June (left) and July (right) 2023 surveys along the north-south transects shown in Figure 2-11. Dots (nutrients) and lines (fluorescence) indicate the sampling depths and downcast profile in situ depths. The yellow line indicates the approximate depth of the pycnocline.

2.3.2 Phytoplankton Biomass

Phytoplankton biomass (vertically summed chlorophyll concentrations, or areal chlorophyll) in Massachusetts Bay typically shows a seasonal pattern, with elevated values during winter/spring, and then again during the fall, as seen in the historical results (shaded regions) in **Figure 2-14**. In February 2023, elevated chlorophyll levels were observed across the bay, particularly at farfield station F22 where they reached the highest February level observed over the monitoring program. Chlorophyll concentrations were highest at deeper depths at offshore stations F22, N04, and N07 indicative of a senescent bloom. As noted above, the low SiO_4 concentrations observed in February indicate a diatom bloom.

Chlorophyll levels decreased to near historic minima across the bay in March 2023. However, in April concentrations increased dramatically – especially at the deeper offshore stations (**Figure 2-14** and **Figure 2-16**). The high chlorophyll concentrations marked the beginning of the extraordinary regional *Tripos muelleri* bloom. This bloom resulted in remarkably high chlorophyll and POC levels. Chlorophyll concentrations remained well above the long-term maxima at most stations from April to July 2023. POC levels were even higher relative to the long-term maxima – often as much as double the previously observed maximum concentrations (**Figure 2-15**). This is because *T. muelleri* are a large-celled phytoplankton species (200-400 µm) with levels of biomass carbon (10-50 ng C $cell^{-1}$) orders of magnitude higher than the more abundant microflagellates and most diatoms.

MODIS imagery and NERACOOS Buoy A01 fluorescence data are useful in filling the information gaps between surveys. High chlorophyll levels were measured in the surface waters at the buoy after the March survey, peaking at over 20 µg L^{-1} in late April and early May as observed during the MWRA surveys (**Figure 2-17**). The chlorophyll fluorescence at the buoy began decreasing by late May but remained relatively high (6-12 µg L^{-1}) through July.

There was a sharp decline in chlorophyll and POC concentrations from June to July as the *Tripos* bloom was ending. From July to October, both chlorophyll and POC concentrations remained close to or below long-term median levels across the bay. The high chlorophyll concentrations observed during the *Tripos* bloom resulted in an exceedance of the summer nearfield seasonal threshold with a value of 163 mg m^{-2}, which is almost double the caution level of 89 mg m^{-2} (**Table i**). The 2023 annual chlorophyll caution threshold was also exceeded with an average of 116 mg m^{-2} being slightly higher than the threshold value of 108 mg m^{-2}. This is the first time the summer seasonal or annual chlorophyll caution thresholds have been exceeded and are the direct result of the extraordinary regional *Tripos* bloom.

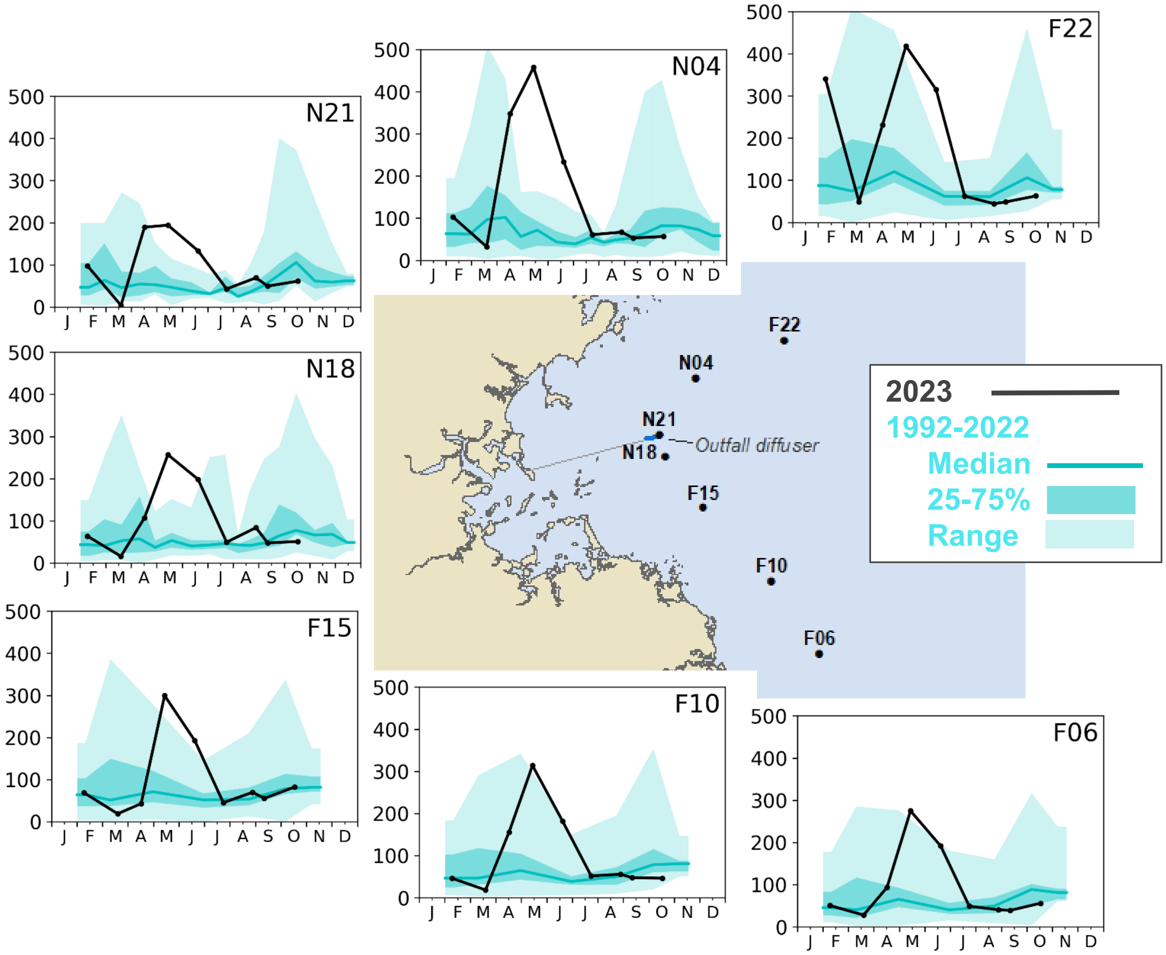


Figure 2-14. Areal chlorophyll from fluorescence (milligram per meter squared [mg m^{-2}]) at representative stations in Massachusetts Bay for 2023 compared to prior years. 2023 results are in black. Results from 1992–2022 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

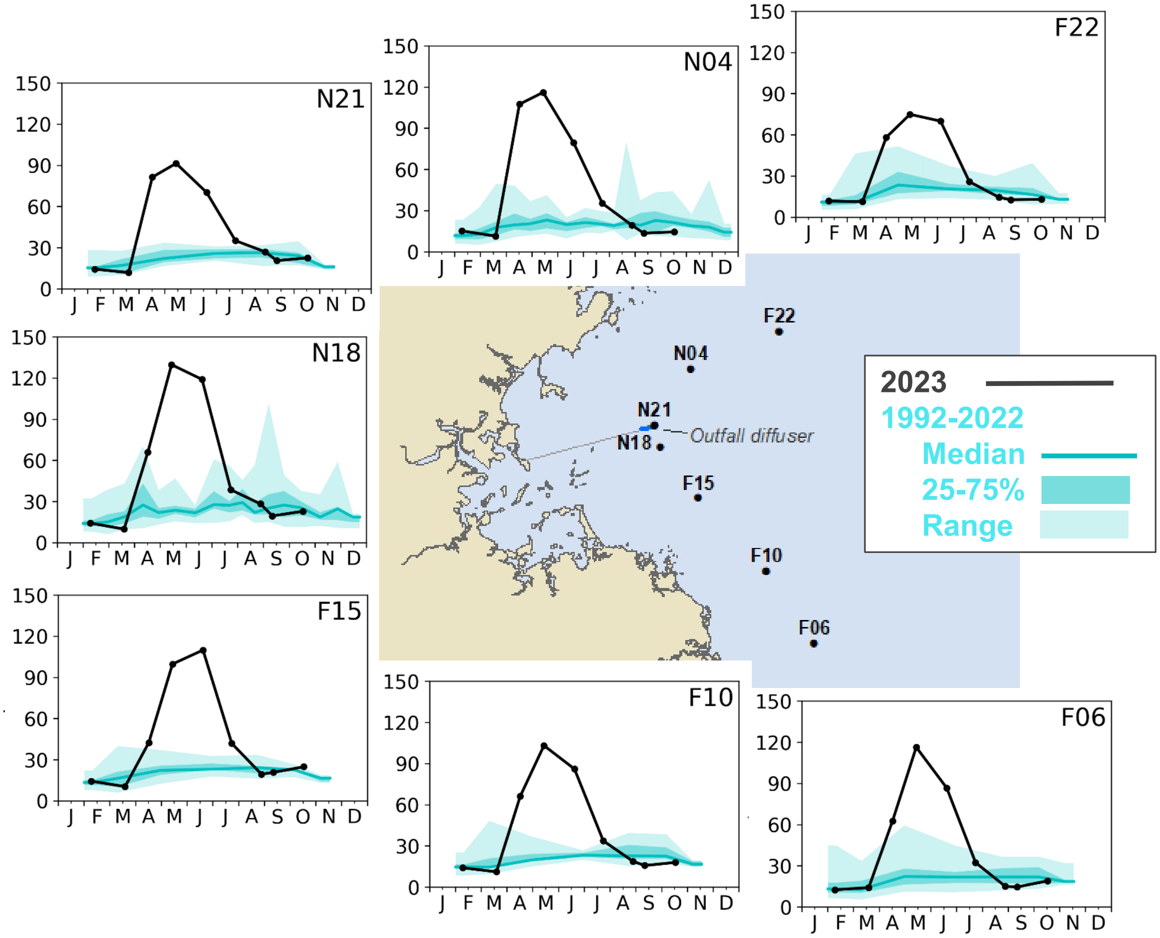


Figure 2-15. Particulate organic carbon (µM) at representative stations in Massachusetts Bay for 2023 compared to prior years. 2023 results are in black. Results from 1992–2022 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

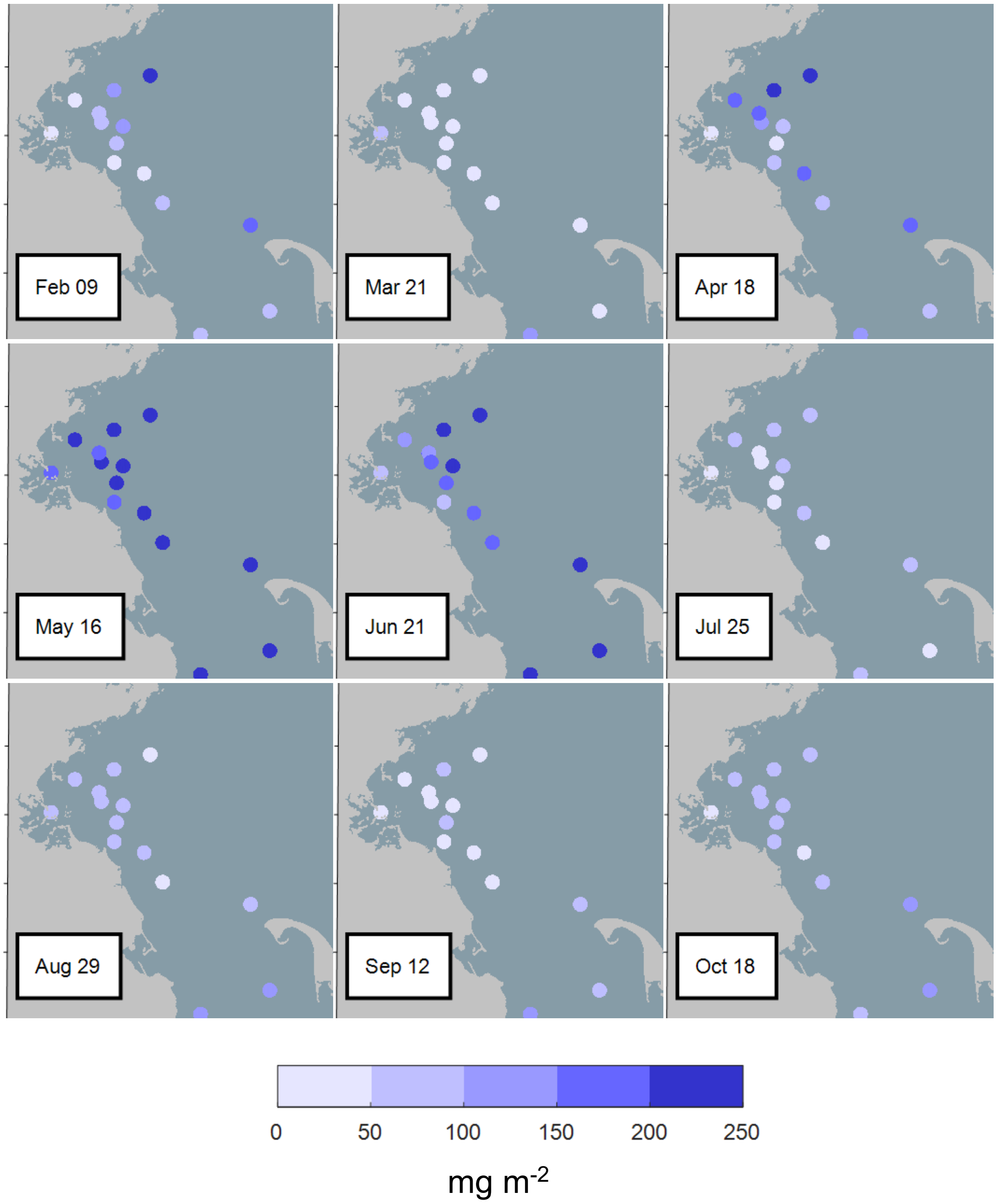


Figure 2-16. **Areal chlorophyll (mg m^{-2}) by station in Massachusetts and Cape Cod Bays in 2023.**

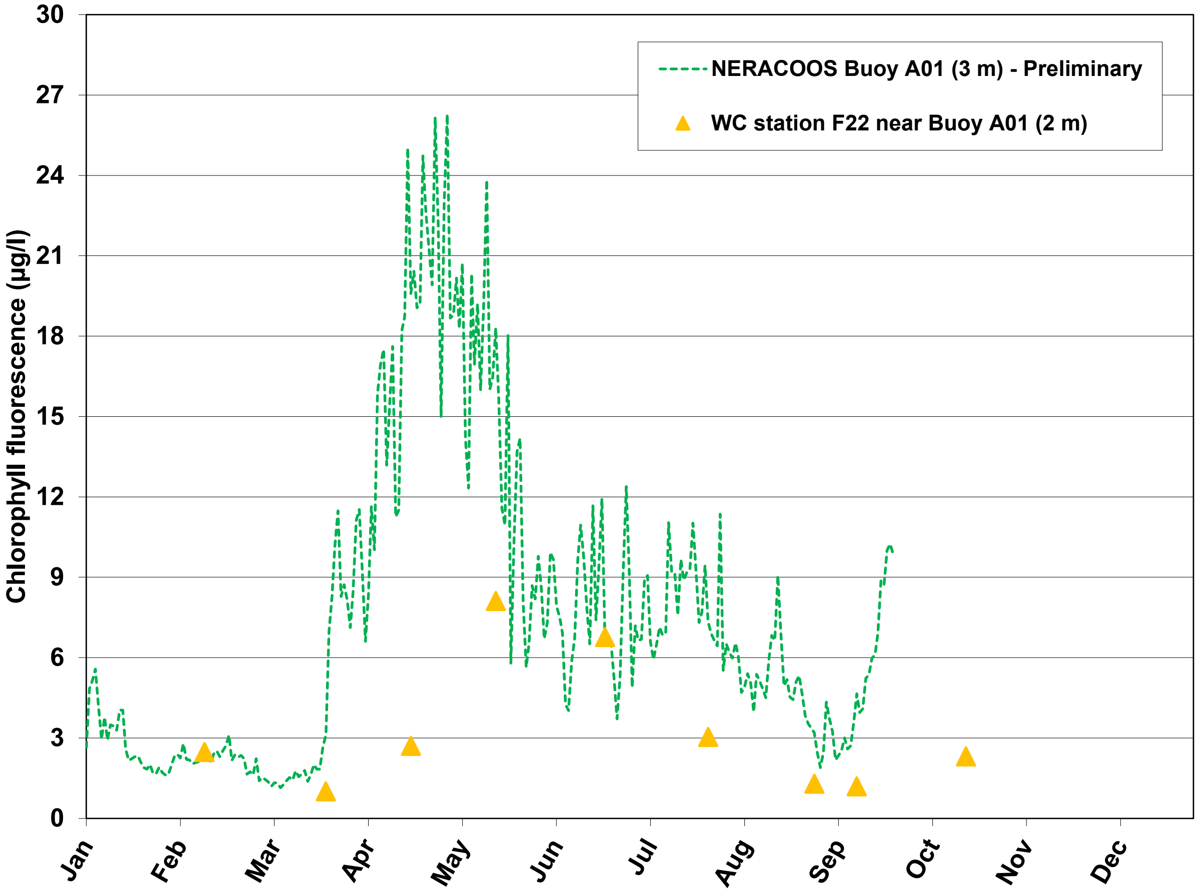


Figure 2-17. Surface water chlorophyll (µg L^{-1}) from fluorescence at Buoy A01 (dashed green line) and water samples at nearby water column (WC) station F22 (yellow symbols) in 2023.

2.4 BOTTOM WATER DISSOLVED OXYGEN

Typically, bottom water DO declines at a relatively constant rate in Massachusetts and Cape Cod Bays from winter/spring maxima to September or October annual minima, but in recent years mixing events have punctuated this seasonal decline. In 2023, bottom water DO levels were low in March and rapidly declined from April through June with levels well below the historic minimum at most stations (**Figure 2-18** and **Figure 2-19**). Upwelling or mixing in July and August led to a leveling off of the decline, and given the historically low bottom water DO levels in June, the 2023 DO depletion rate was the lowest observed for the monitoring program at 0.008 mg L^{-1} d^{-1}, well below the Contingency Plan threshold of 0.037 mg L^{-1} d^{-1} (**Table i**). However, the bottom water DO levels were below long-term minimum at many stations from June to October and thresholds were exceeded in July, September, and October. Low DO values were also observed at stations in Cape Cod Bay with minima of <4 mg L^{-1} at station F02 from July to September 2023. Fortunately, unlike 2019 and 2020, there were no observations of hypoxic to anoxic conditions in shallower, nearshore Cape Cod Bay waters. The sharp decline in bottom water DO from April to July and the moderation of the rate of depletion was also observed at the NERACOOS Buoy A01 (**Figure 2-20**).

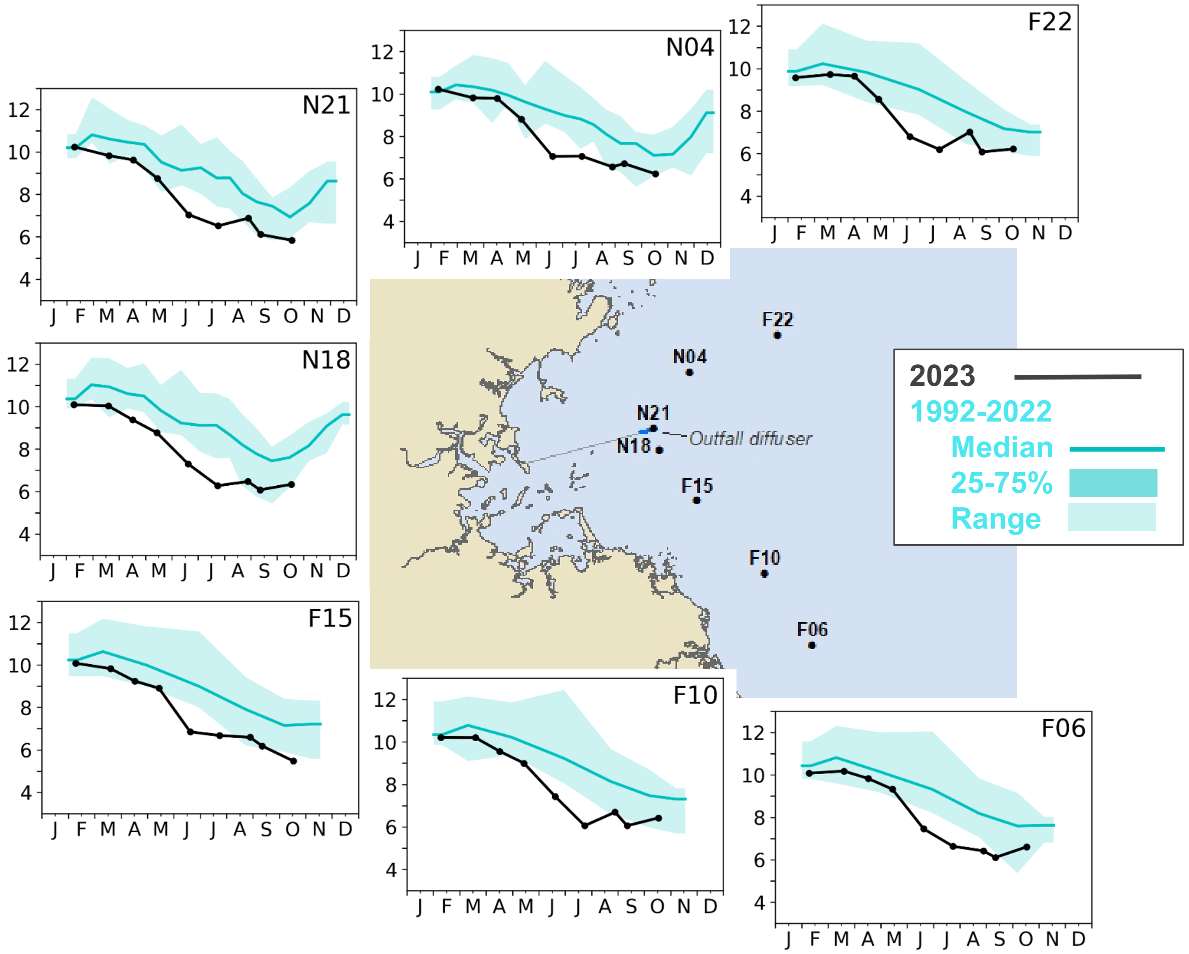


Figure 2-18. Survey bottom water dissolved oxygen concentration (mg L^{-1}) at selected stations in Massachusetts Bay for 2023 compared to prior years. 2023 results are in black. Results from 1992–2022 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

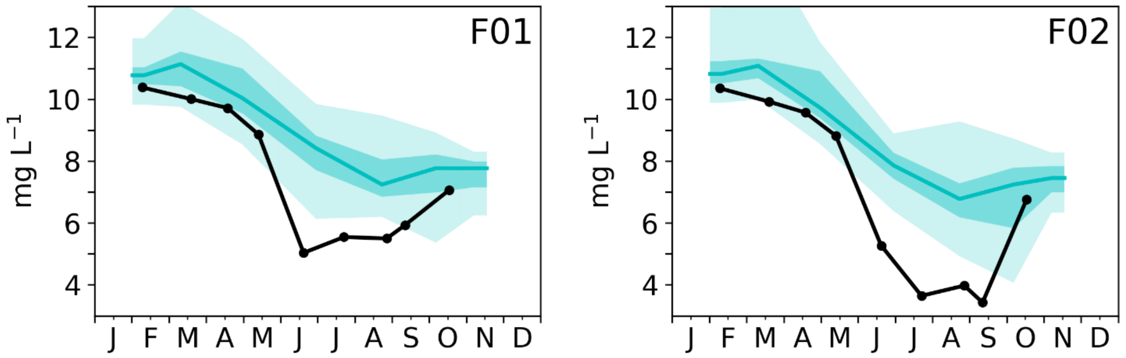


Figure 2-19. Survey bottom water dissolved oxygen concentration (mg L^{-1}) at selected stations in Cape Cod Bay for 2023 compared to prior years. 2023 results are in black. Results from 1992–2022 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

A combination of factors played a role in the low levels of bottom water DO in 2023 – both physical (temperature) and biological (*Tripos* bloom). Water temperatures were very warm compared to historical levels in February and March 2023 (**Figure 2-1** and **Figure 2-2**), which led to bottom water DO levels in February that were below the long-term median and lower levels in March and April that were within the lower quartile of historic observations across Massachusetts and Cape Cod Bays (**Figure 2-18** and **Figure 2-19**).

Interestingly, surface water DO concentrations increased dramatically from March to April and remained higher than typically observed in May and June. This increase was associated with the *Tripos* bloom and elevated rates of primary production. Over this same period, bottom water DO concentrations rapidly declined to levels well below the historic minimum at most stations from April through June. The rapid decrease and low bottom water DO levels were likely due to biological decomposition of senescent *Tripos* biomass, leading to oxygen consumption in the bottom waters. An additional contributing factor was the strong stratification of the water column due to warm water temperatures and low surface salinities. The stratification prevents dissolved oxygen in the surface layers of the ocean from replenishing deep layers.

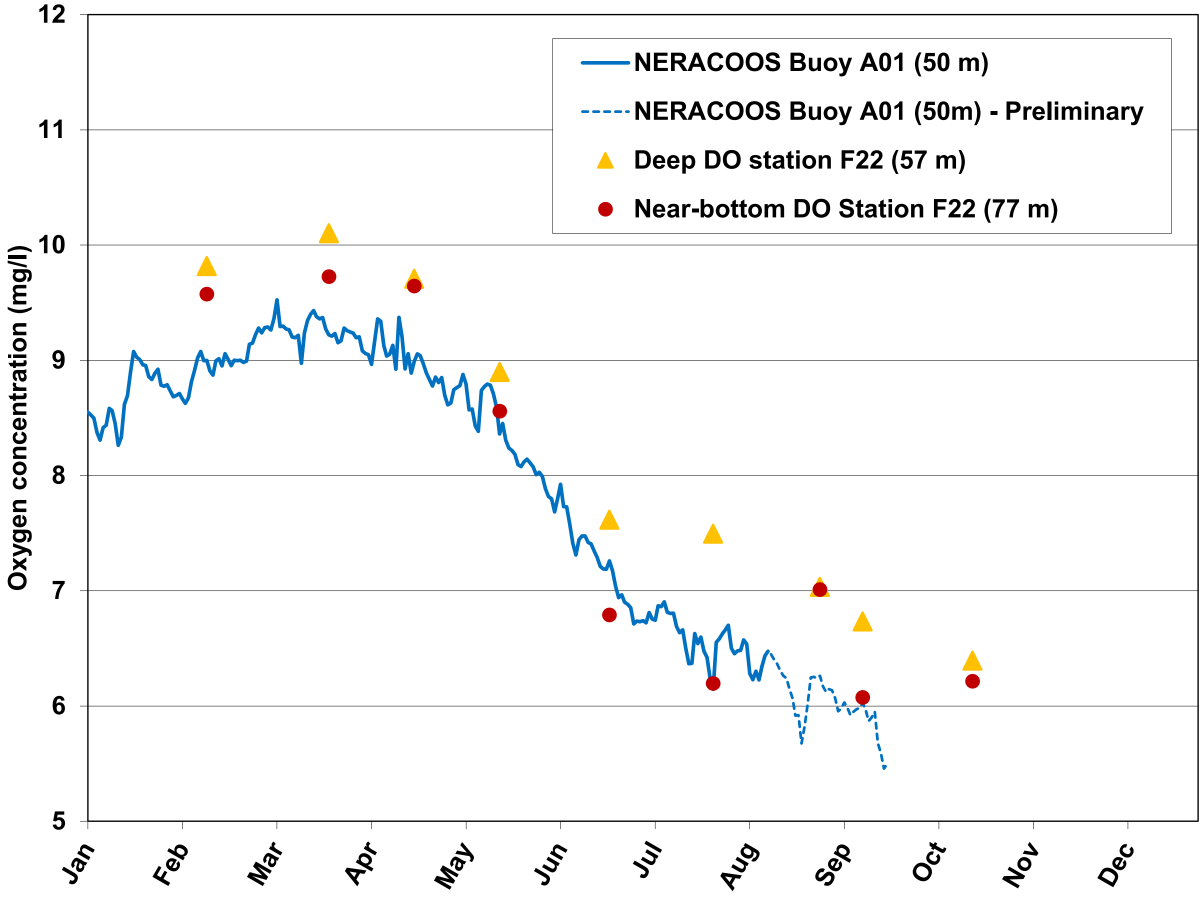


Figure 2-20. Time-series of dissolved oxygen concentration (mg L^{-1}) at Buoy A01 (50 m) and at the deep and near-bottom sampling depths (~57 and ~77 m) at station F22 in 2023. The buoy values are daily means.

2.5 PHYTOPLANKTON ABUNDANCE

Overall, total phytoplankton measured in 2023 was near long-term mean levels (**Figure 2-21**). Total phytoplankton abundance was dominated by elevated microflagellate and dinoflagellate abundance throughout the year, the major regional *Tripos muelleri* bloom April through August, and a series of minor blooms of *Skeletonema* spp. during the summer and pennate diatoms (*Asterionellopsis glacialis* and *Thalassionema nitzschioides*) during autumn. Total phytoplankton levels in the nearfield (stations N18 and N04) averaged 941,557 cells L^{-1} during 2023 compared to levels of 795,581 cells L^{-1} observed during the previous five years (2018-2022; **Table 2-1**). This represents a 1.2-fold increase ($p = 0.064$) and resulted in 2023 nearfield total phytoplankton being the 23rd ranked in abundance of 32 years monitored. Elevated 2023 total phytoplankton abundance is evident as an uptick in the long-term deseasonalized trend, with total phytoplankton abundance recently (2021-2023) trending upward during after approximately a decade of declines and low levels (**Figure 2-22**).

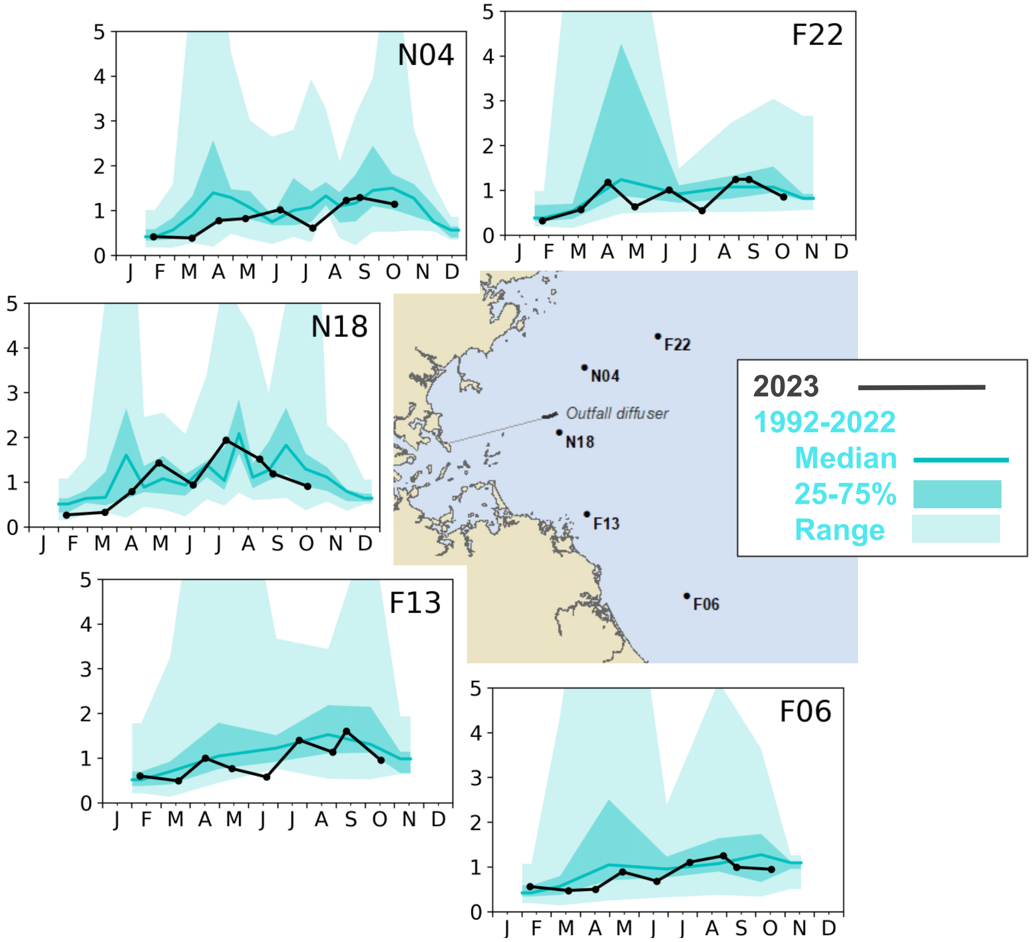


Figure 2-21. Total phytoplankton abundance (millions of cells L^{-1}) at selected stations in 2023 compared to prior years. 2023 results are in black. Results from 1992-2022 are in cyan: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range. The map insert highlights stations shown here and in subsequent phytoplankton and zooplankton figures, where an extended plankton dataset is available.

Table 2-1. 2023 annual mean nearfield phytoplankton abundance (cells L^{-1}) ranked for 1992-2023 period and compared to 2018-2022 abundances for major groups and species. Data are from the surface and chlorophyll maximum sampling depths at stations N16/N18. Significant differences compared to 2018-2022 means highlighted in blue/bold.

Group	2023 Rank (out of 32 years)	2023 (cells L^{-1})	2018-2022 (cells L^{-1})	% change	p value[1]
CENTRIC DIATOM	26th	103,468	109,342	-5%	0.7954
Chaetoceros	18th	5,488	4,900	12%	0.7866
Dactyliosolen fragilissimus	23rd	5,453	3,688	48%	0.4392
Skeletonema spp. complex	13th	32,416	36,816	-12%	0.8116
Thalassiosira	30th	4,944	10,564	-53%	0.0643
MICROFLAGELLATES	12th	**657,498**	**496,601**	**32%**	**0.0004**
Phaeocystis pouchetii	28th	0	17,089	-	0.3873
CRYPTOPHYTES	24th	76,538	68,266	12%	0.4079
DINOFLAGELLATES	9th	76,895	71,319	8%	0.7804
Tripos	1st	**25,747**	**1,626**	**1,483%**	**<0.0001**
Dinophysis	32nd	16	667	-98%	0.3989
Prorocentrum	5th	13,921	17,778	-22%	0.7791
PENNATE DIATOM	16th	18,761	20,680	-9%	0.8400
Pseudo-nitzschia	31st	675	13,529	-95%	0.1853
TOTAL PHYTOPLANKTON	23rd	941,557	795,581	18%	0.0640

[1] Differences between values were assessed using the Mann-Whitney non-parametric statistical hypothesis test; p values of ≤0.05 are noted. These are exploratory analyses involving multiple comparisons. Determination of significant changes is complicated by multiple comparison issues and corrections for the associated errors are considered beyond the scope of the analyses.

Microflagellates (spherical cells less than 10 μm diameter) are the most abundant phytoplankton group in the Massachusetts Bay monitoring area, comprising ~79% of phytoplankton cells in 2023. Microflagellate abundance was near or slightly above long-term mean levels for most of 2023, with an exception in July 2023 which had markedly reduced microflagellate abundance at many stations (data not shown). Microflagellate abundance, relative to long-term mean levels, resulted in 2023 nearfield microflagellate abundance (657,498 cells L^{-1}) that was 1.3-fold the level (496,601 cells L^{-1}) observed during 2018 to 2022 and ranked 12th of 32 years (**Table 2-1**). This was a significant increase in nearfield microflagellate abundance in 2023 versus 2018-2022.

Following the pattern observed in recent years, 2023 was not a *'Phaeocystis year'* in Massachusetts Bay. *Phaeocystis pouchetii* was not observed in any nearfield samples collected and was only observed in three of 209 (equivalent to 1.4%) phytoplankton samples analyzed for 2023. Maximum *Phaeocystis* abundance during 2023 was 18,054 cells L^{-1} observed in the surface water at station F02 in Cape Cod Bay in April. Note maximum *Phaeocystis* abundances of tens of millions of cells L^{-1} have been recorded in Massachusetts Bay during major bloom years. Historically, *Phaeocystis* is one of the dominant phytoplankton taxa in the bay and low *Phaeocystis* abundance observed during the last 10 years has contributed to the long-term decline in total phytoplankton abundance relative to the levels observed during the early 2000s (**Figure 2-22**).

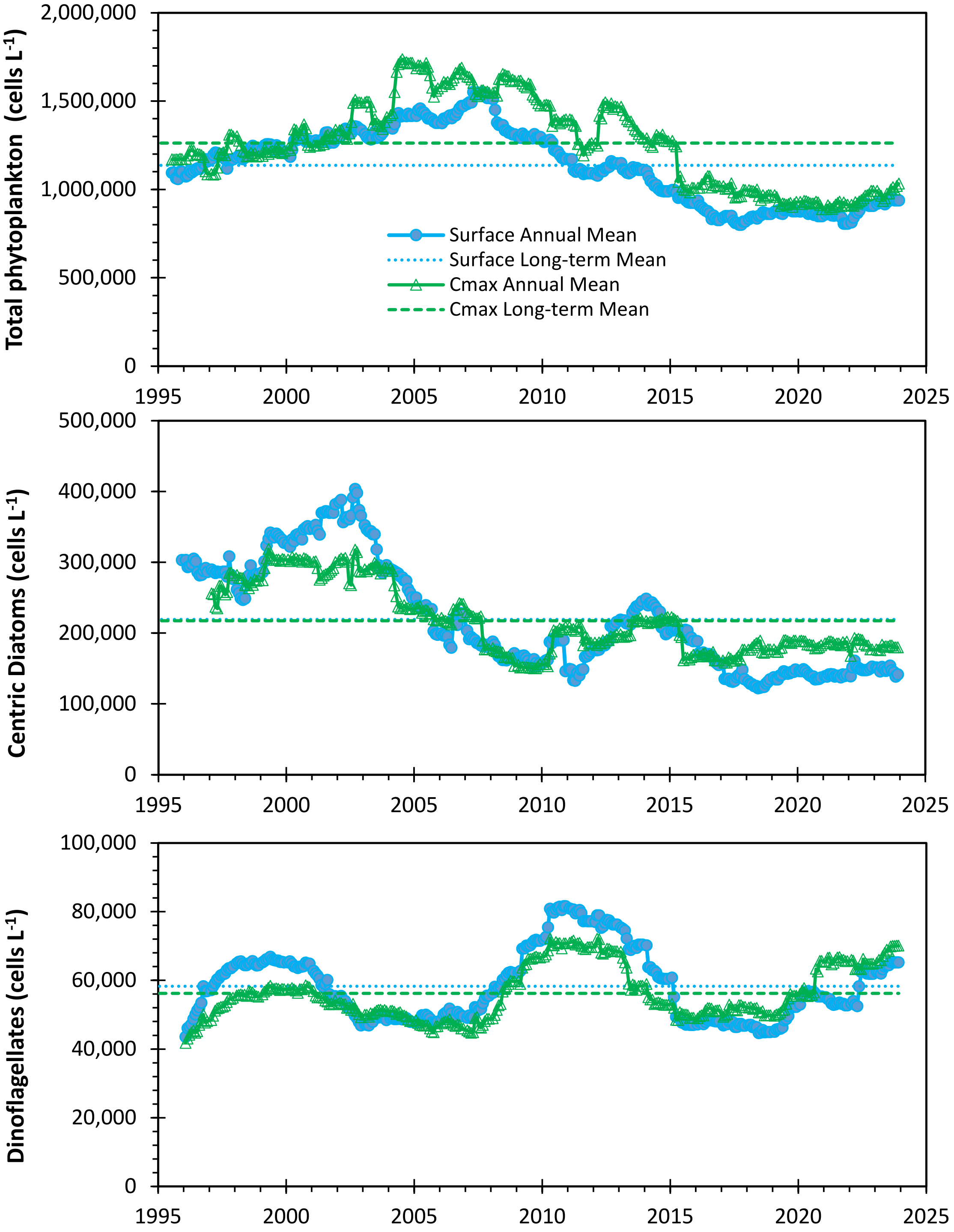


Figure 2-22. Estimated long-term (1992-2023) abundances of phytoplankton groups in the nearfield region (stations N04 and N16/N18) derived from time series analysis. Each panel shows the deseasonalized annual mean abundance at the surface (blue) and at the chlorophyll maximum depth (green) during 1992-2023. Horizontal dashed lines are 1992-2023 mean abundances. Panels show total phytoplankton (top panel), centric diatoms (middle panel), and dinoflagellates (bottom panel). Monthly deseasonalized abundance estimates have been smoothed with a 15% smoothing window equivalent to the ~48 months preceding the sample date (Broekhuizen and McKenzie 1995).

Centric diatom abundance was below normal in the nearfield during 2023, continuing the trend observed during the past decade (**Figure 2-22**). Winter centric diatom abundance in the nearfield (stations N04 and N18) was approximately one-third the 2018-2022 levels. Spring abundance was above long-term mean levels at several stations due to a bloom of *Skeletonema* spp. that reached a maximum of 1.2 x 10^6 cells L^{-1} at station F22 in April 2023. Summer blooms of *Skeletonema* spp. and *Dactyliosolen fragilissima* were observed, especially at Boston Harbor station F23 where *Skeletonema* spp. reached abundance levels of approximately 450,000 cells L^{-1} during August 2023. Overall, centric diatoms at nearfield stations N04 and N18 (both depths combined) had an annual mean abundance of 103,468 cells L^{-1} during 2023 compared to levels of 109,342 cells L^{-1} observed during 2018-2022 and ranked 26th of the 32 years of monitoring (**Table 2-1**), continuing the long-term decline in centric diatom abundance (**Figure 2-22**).

The April 2023 *Skeletonema* peak continues a recent pattern of increased winter-spring *Skeletonema* abundance. *Skeletonema* spp. are morphologically similar, and the taxa formerly known as *Skeletonema costatum* contains several molecularly distinct species that are not easily discerned via light microscopy (Kooistra et al. 2008). Further, these formerly unidentified cryptic *Skeletonema* spp. have distinct temperature and other environmental preferences for maximum growth (Canesi and Rynearson, 2016). In Narragansett Bay, shifts in the *Skeletonema* annual cycle have been associated with winter warming (Borkman and Smayda, 2009a) and variation in ocean currents (the Gulf Stream; Borkman and Smayda, 2009b). The recent shift in *Skeletonema* annual pattern may be indicative of similar changes, possibly regime changes, in oceanographic forcing in Massachusetts Bay. This is consistent with the warmer temperatures that have been observed in the bay as discussed in Section 2.1.

Pennate diatom abundance was below long-term mean levels for much of 2023, but this low abundance was offset by a July-August bloom of *Thalassionema nitzschioides* and *Asterionellopsis glacialis* that reached approximately 200,000 cells L^{-1} at several stations (data not shown). Of note, 2023 abundance of the potentially toxigenic harmful algal bloom (HAB) genera *Pseudo-nitzschia* was among the lowest levels (31st rank of 32 years) observed during the 1992-2023 monitoring program (**Table 2-1**). In stark contrast to 2023, *Pseudo-nitzschia* abundance was high during 2022 (#1 rank of 1992-2023) due to a March 2022 *Pseudo-nitzschia* bloom that reached 500,000 cells L^{-1} at multiple stations. Reduced 2023 Massachusetts Bay *Pseudo-nitzschia* abundance appears to be part of a regional pattern with low *Pseudo-nitzschia* abundance noted by shellfish-HAB phytoplankton monitoring programs from Nova Scotia to Rhode Island during 2023 (Northeast HAB Conference, March 2024).

Dinoflagellates were more abundant than the long-term average in the Massachusetts Bay nearfield area during most of 2023 (**Figure 2-23**). This was due in large part to an extraordinary bloom of *Tripos muelleri* that dominated the phytoplankton community from April through July 2023 (**Figure 2-24**). This *Tripos* bloom was regional, with phytoplankton monitoring programs noting elevated *Tripos* abundance from Maine, New Hampshire, Massachusetts, and Rhode Island during summer 2023 and is discussed in detail in Section 3. In Massachusetts Bay, *T. muelleri* abundance typically reaches maximum abundance of approximately 10,000 cells L^{-1} in late summer. *Tripos muelleri* had a much different bloom pattern during 2023; it had elevated abundance beginning in April, reached peak abundance in May or June and, most notably, reached abundance levels that were 13 to 20 times the long-term (1992-2022) mean levels previously observed in Massachusetts Bay. *Karenia mikimotoi*, which appeared in the area in 2017 with blooms associated with low DO in Cape Cod Bay (Scully et al. 2022) was present in only low levels during 2023. Dinoflagellates have a long-term cyclical abundance pattern in Massachusetts Bay (**Figure 2-22**, bottom) and abundance of several dinoflagellates (*Prorocentrum* spp., small *Gymnodinium* spp., *Heterocapsa* spp.) was elevated during 2023. The elevated abundance of these species and the *Tripos muelleri* bloom resulted in 2023 being ranked 9th of 32 years for dinoflagellate abundance (**Table 2-1**).

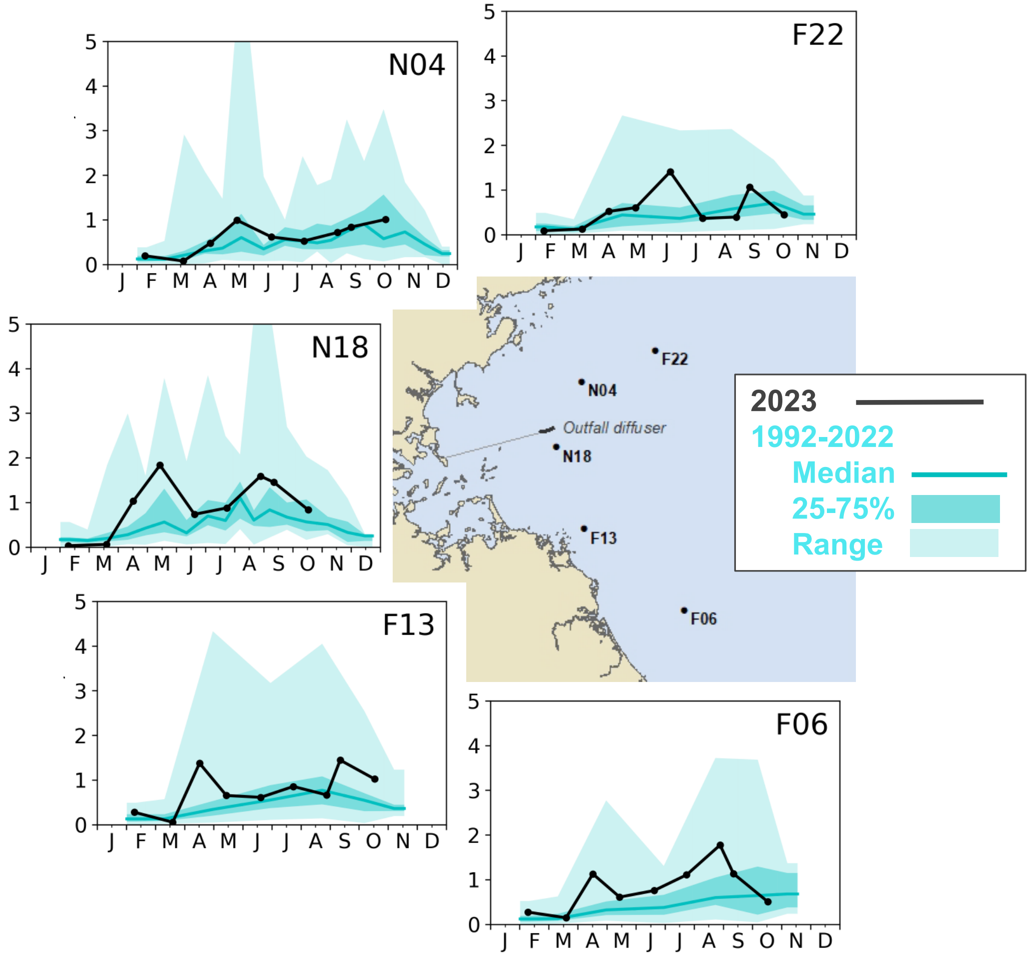


Figure 2-23. Dinoflagellate abundance (100,000 cells L^{-1}) at selected stations in 2023 compared to prior years. 2023 results are in black. Results from 1992-2022 are in cyan: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range.

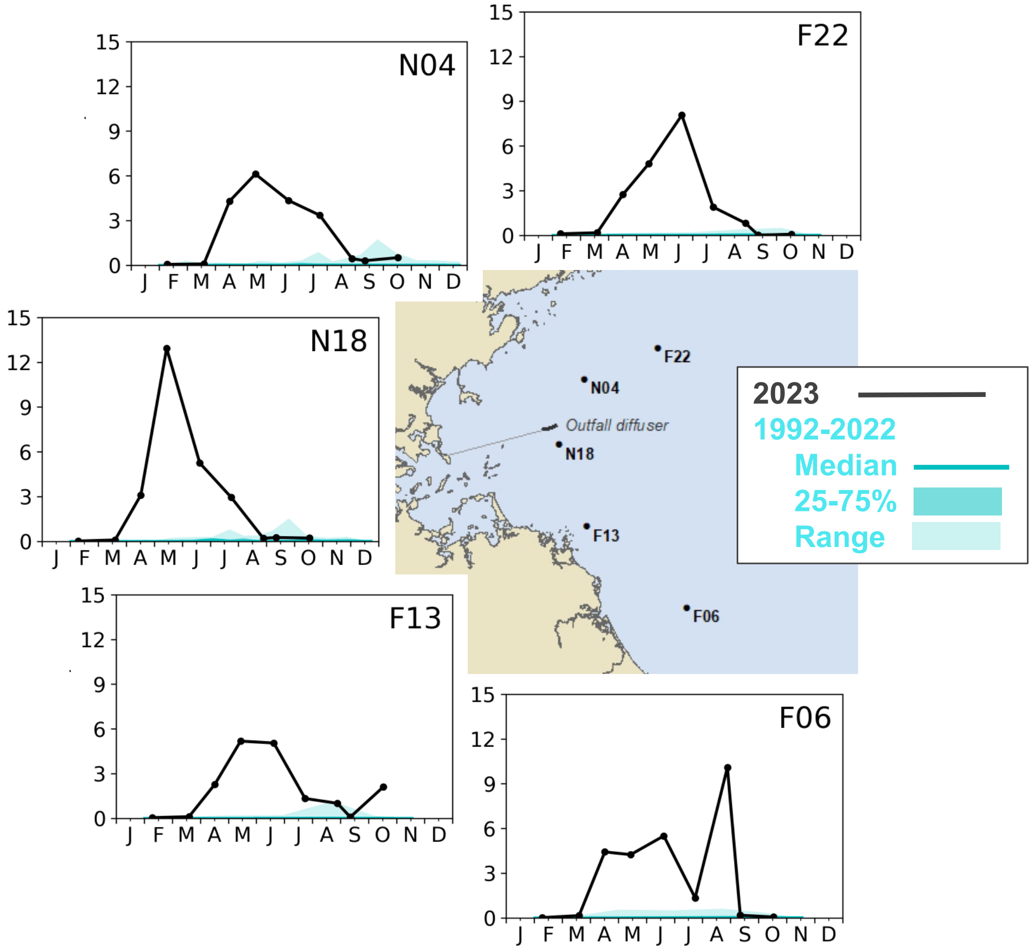


Figure 2-24. ***Tripos muelleri*** **abundance (10,000 cells L^{-1}) at selected stations in 2023 compared to prior years.** 2023 results are in black. Results from 1992-2022 are in cyan: line is the 50th percentile, dark shading spans the 25th to 75th percentile, and light shading spans the range.

There were no threshold exceedances for nuisance species in 2023 (**Table i**). *Pseudo-nitzschia* have not been an issue for shellfish toxicity in Massachusetts Bay and abundances of this potentially toxic species in 2023 were orders of magnitude lower than threshold levels. Species of *Pseudo-nitzschia* have exhibited blooms and toxicity in the Gulf of Maine recently and continue to be the focus of study in the region. *Alexandrium* abundances were very low in Massachusetts Bay in 2023 (**Figure 2-25**). The highest *Alexandrium* abundance of 32 cells L^{-1} in 2023 was observed at station N01 in April and was well below the rapid response and contingency thresholds of 100 cells L^{-1}. Unsurprisingly, PSP toxicity was undetectable in Massachusetts coastal waters from the New Hampshire border to Cape Ann and within Massachusetts Bay in 2023. This was also the case throughout the Gulf of Maine (eastern and western) with very low *Alexandrium* abundances and no PSP toxicity except for a few embayments along the eastern side of Cape Cod. It is unclear why there was not an *Alexandrium* bloom in 2023 as the abundances in April, though low, were elevated versus historic levels (**Figure 2-25**). The physical oceanographic conditions were certainly conducive for dinoflagellates in April and May 2023 with strong stratification (**Figure 2-5**) which was a factor in the initiation and growth of the *Tripos muelleri* bloom. It has been postulated that the *Tripos* bloom may have limited *Alexandrium* growth through allelopathic mechanisms or nutrient limitation due to the extremely low NO_3 concentrations. This continues to be the focus of researchers at many institutions in the Gulf of Maine region.

There has been a trend of generally low *Alexandrium* abundance in the western Gulf of Maine extending back to 2009 (D.M. Anderson, unpub data). The pattern in Massachusetts Bay is more variable, however, with low levels of abundance from 2013 to 2019, but intermittent high and low values from 2020 – 2023. In contrast, *Alexandrium* abundance and PSP toxicity records show an increase in Cape Cod estuaries beginning about 2000 and continuing to the present. This difference between the decline in the widespread coastal *Alexandrium* blooms in the Gulf of Maine and the increases seen in Cape Cod estuaries and embayments is the subject of ongoing research.

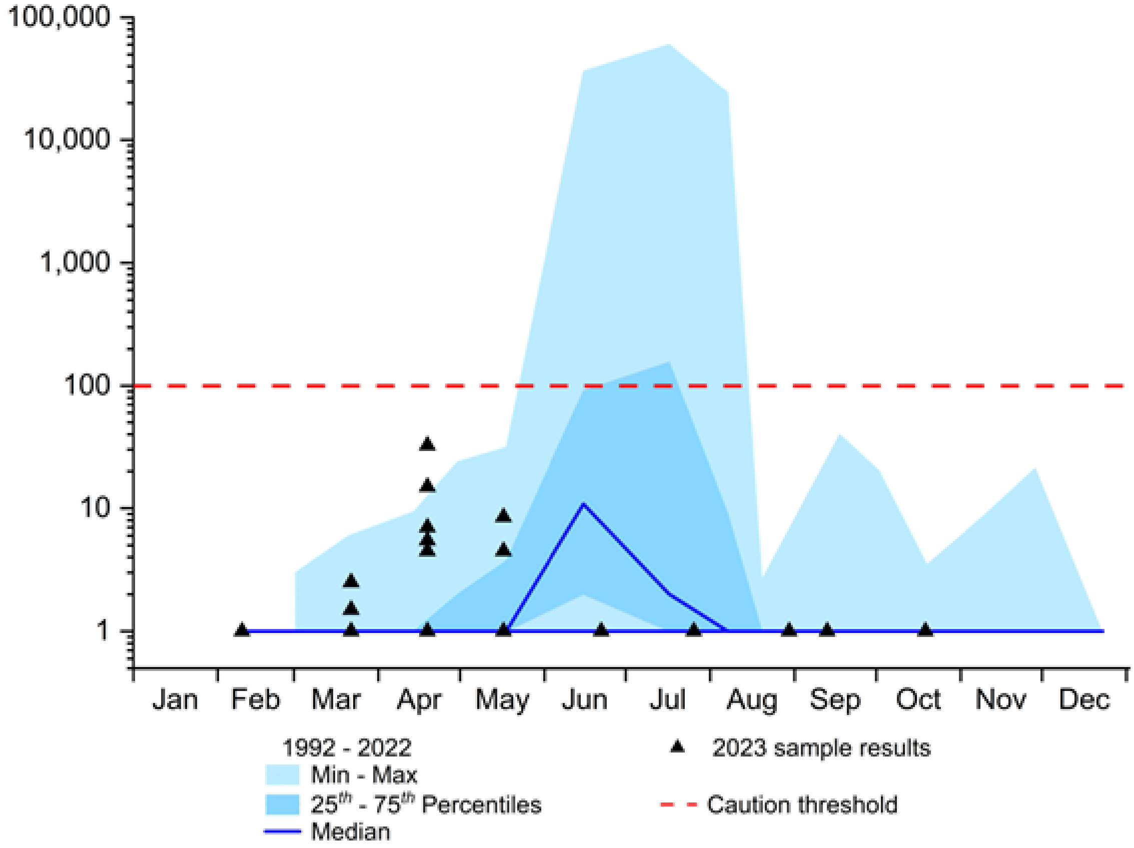


Figure 2-25. Nearfield sample abundance (cells L^{-1}) of *Alexandrium* in 2023 compared to prior years. Note the log scale. 2023 results are in black. Results from 1992–2022 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

2.6 ZOOPLANKTON ABUNDANCE

Zooplankton taxa, seasonal patterns, and abundances in 2023 were generally similar to those seen the most previous years of the monitoring program (**Figure 2-26**). Seasonal patterns of abundance were normal, with increases from winter lows through to spring and summer peaks, followed by fall declines. Total zooplankton abundance was high in June and July, due primarily to increases in bivalve veliger larvae. This was also apparent in the data for "Other Zooplankton (Meroplankton)" which was dominated by radiolarians in October 2023.

There were elevated abundances of copepod nauplii in July, and copepod nauplii were part of the elevated total zooplankton peaks in October, particularly at stations F13, F22, and N04. Abundances of copepod adults + copepodites were driven primarily by June/July peaks of copepodites of *Centropages* spp. and *Oithona similis,* with high abundances of *O. similis* in October at station F13 (**Figure 2-27**). *Calanus finmarchicus* were mainly present in March/April at stations farther offshore at levels close to the long-term median. *Acartia* spp. were found in Boston Harbor, with highest abundances from March to June that were well above the long-term median and declined to much lower abundances in July and August (data not shown).

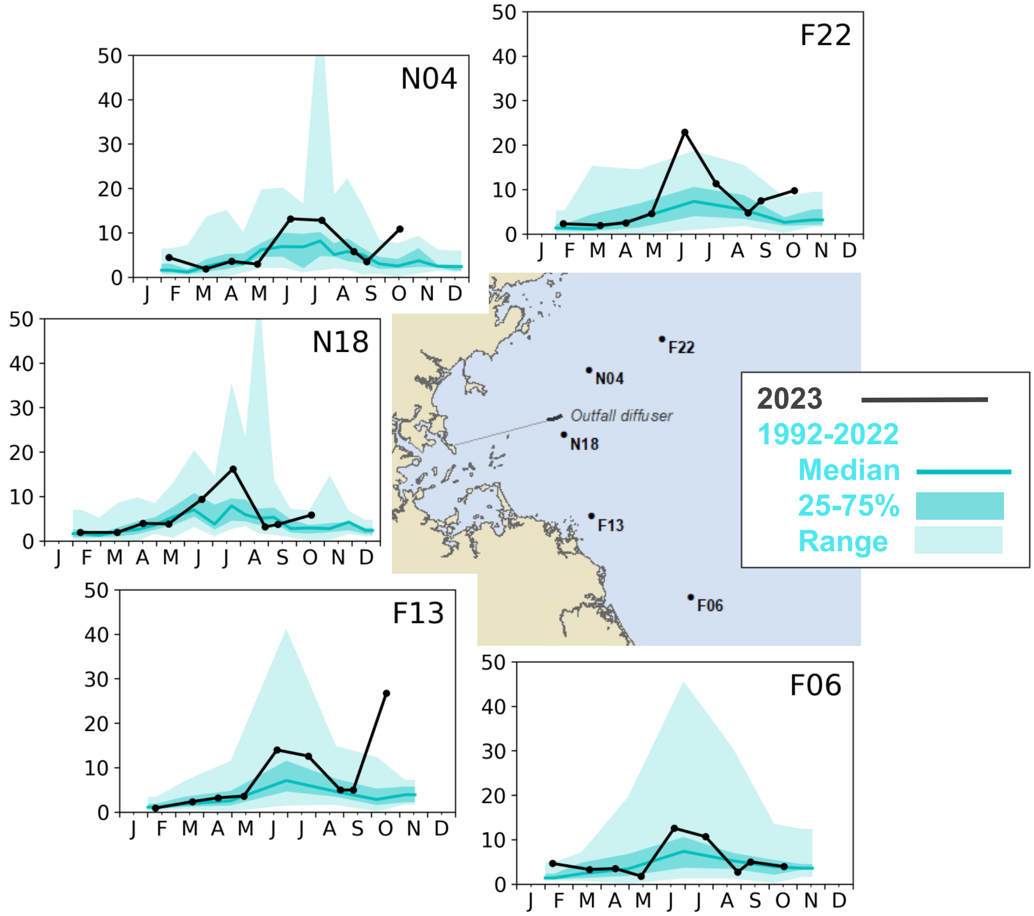


Figure 2-26. Total zooplankton abundance (10,000 individuals m^{-3}) at selected stations in Massachusetts Bay for 2023 compared to prior years. 2023 results are in black. Results from 1992–2022 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range. The peak values exceeding the maximum of the y-axis were measured in 2015.

Peak abundances of total zooplankton in June and July 2023 were driven by elevated abundances of “Other Zooplankton” or meroplankton, including bivalve and gastropod veligers (**Figure 2-28**). This spawning event was second only to the extreme abundances observed in summer of 2015 when the maximum abundance for the monitoring program was observed. There were also high abundances of meroplankton in October 2023, which was dominated by radiolarians. Radiolarians were also observed in August/September 2020, July/November 2021, and July 2022 after no observations before 2020. The presence of radiolarians, which are more oceanic and warm water taxa than those in the MWRA sampling area, aligns with the warmer temperatures recorded for 2023.

It may be that Massachusetts Bay is showing signs of warming associated with the northward extension of the Gulf Stream, which has been reported in recent years (Townsend et al 2023; Goncalves Neto et al. 2021). This is an important trend to be considered in many Massachusetts Bay monitoring parameters going forward.

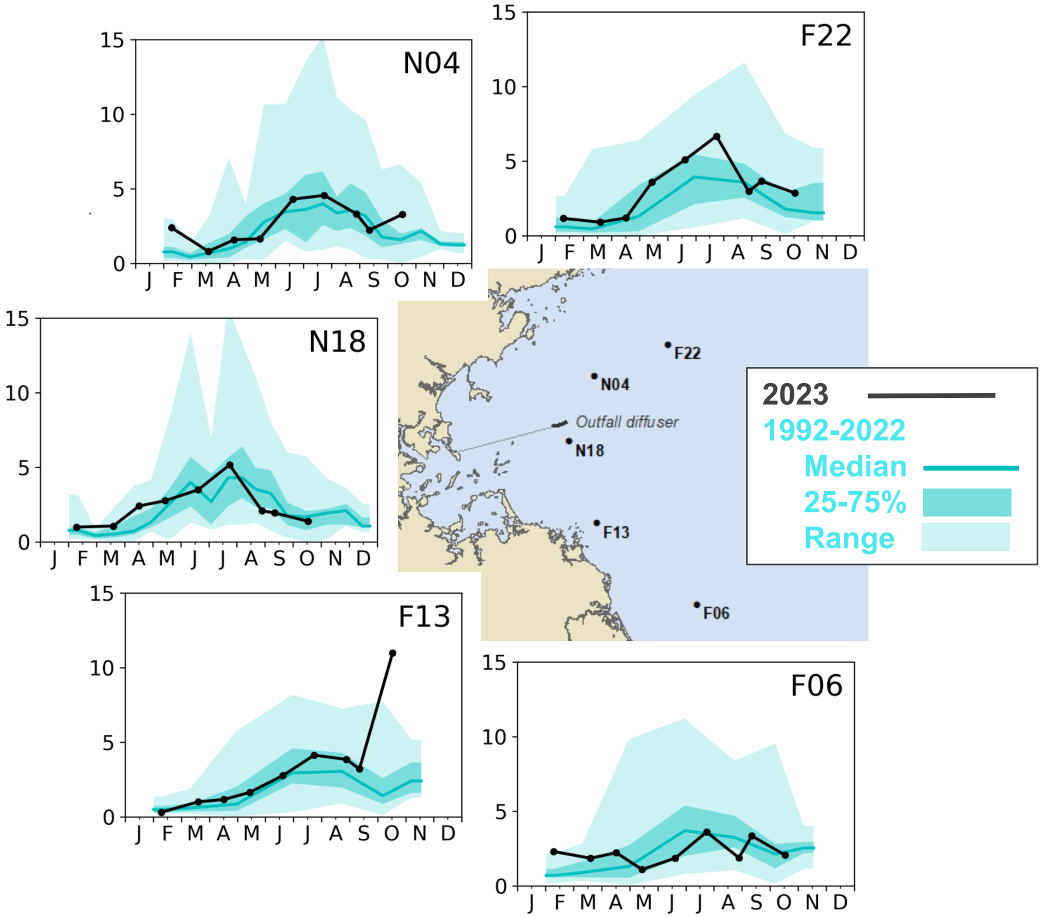


Figure 2-27. **Total copepod adults and copepodites (10,000 individuals m^{-3}) at selected stations in Massachusetts Bay for 2023 compared to prior years.** 2023 results are in black. Results from 1992–2022 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range. The peak values exceeding the maximum of the y-axis were measured in 2015.

There were no apparent changes in normal patterns of zooplankton abundance and composition related to the massive bloom of the dinoflagellate *Tripos muelleri* (formerly *Ceratium tripos*). Previous analyses in the MWRA sampling area indicated that dinoflagellates of the genus *Ceratium/Tripos* were associated with strong stratification, as was measured during spring and summer of 2023. There is almost no published information on zooplankton grazing on dinoflagellates of the genera *Ceratium*/*Tripos*, but the limited information available suggests dinoflagellates of this genus are not easily grazed by copepods (Falkowski et al. 1980), with more successful grazing by microzooplankton protists and marine cladocerans rather than copepods (Nielsen, 1991).

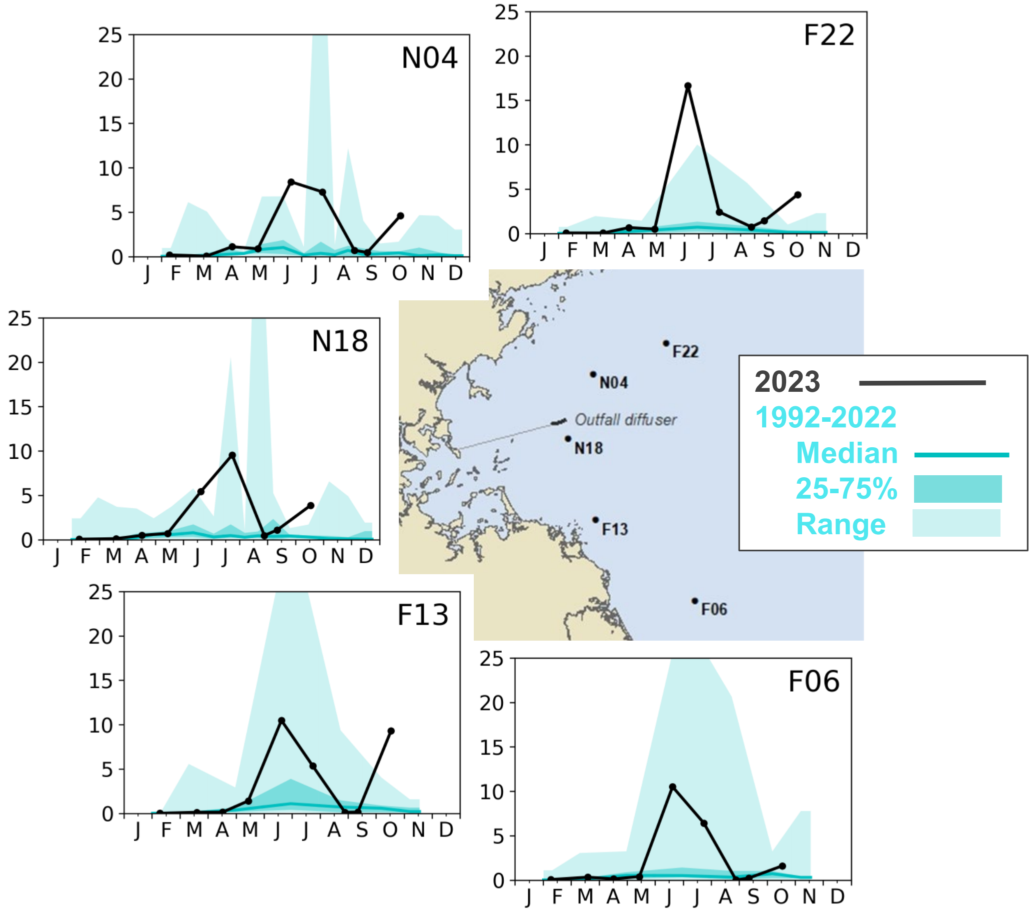


Figure 2-28. Total meroplankton (10,000 individuals m^{-3}) at selected stations in Massachusetts Bay for 2023 compared to prior years. 2023 results are in black. Results from 1992–2022 are in cyan: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range. The peak values exceeding the maximum of the y-axis were measured in 2015.

2.7 MARINE MAMMAL OBSERVATIONS

Observing marine mammals during surveys designed and operated for the collection of water quality data places limitations on the method of observation and on the conclusions that may be drawn from the data. Unlike statistically-based programs or programs that are specifically designed to search for whales (Khan et al. 2018), the MWRA sightings are opportunistic and do not follow dedicated and systematic line transect methodology. Therefore, observations are descriptive and not a statistically robust population census.

In 2023, two minke whales (*Balaenoptera acutorostrata*), one unidentified baleen whale, and seven unidentified whales were observed during the MWRA surveys in Massachusetts Bay (**Table 2-2** and **Figure 2-29**). No North Atlantic right whales were sighted during 2023 surveys. Other marine mammal sightings included 12 harbor seals (*Phoca vitulina*) and nine Atlantic white-sided dolphins (*Lagenorhynchus acutus)*.

MWRA revised its outfall AMP in 2004 and 2011 (MWRA 2004, 2010) to reduce both the number of annual surveys and the monitoring stations sampled during each survey through each revision, and the prime whale habitats of Stellwagen Bank and Cape Cod Bay are no longer included in MWRA's marine mammal observations. Decreases in the number of whale sightings after 2010 are due to reduction of the number and frequency of surveys as well as monitoring stations, and not evidence of a decline in whale populations. These results are summarized in **Table 2-2** and the 2023 results are shown geographically in **Figure 2-29**.

Table 2-2. **Number of whale sightings from 1998 to 2023.** Note that the numbers in this table may not match tables in previous reports, which only reported sightings within the nearfield area of the MWRA outfall.

Year	**Finback whale**	**Humpback whale**	**North Atlantic right whale**	**Fin or Sei whale**	**Minke whale**	**Pilot whale**	**Unidentified baleen whale**	**Unidentified toothed whale**	**Unidentified whale**	**Year Totals**
1998		5	3		7		5		3	23
1999	27	12	2		4		9		5	59
2000	5	22			3	21	11		2	64
2001		4	11		4		3			22
2002	6	9	2		1		2		1	21
2003	1	3			6		4			14
2004	3		3		2				3	11
2005	1	5			17		9		1	33
2006	9	32	1		7		1		4	54
2007	1	7	1		4		1		3	17
2008	5	9	13	1	5		10			43
2009	1	12	1		10		10		4	38
2010	4	9	4		9	1	6	1		34
2011	1				5					6
2012		4	2		1				1	8
2013			4						1	5
2014					2		1			3
2016			2		3					5
2017		2	8		4		3		1	18
2018	1				4		2			7
2019	1	1			1		2	1		6
2020		2	1		4					7
2021	1	2	5		3				2	13
2022		1	5		1		1	1		9
2023					1		2	7		10
Species Totals	**67**	**141**	**68**	**1**	**108**	**22**	**82**	**10**	**31**	**530**

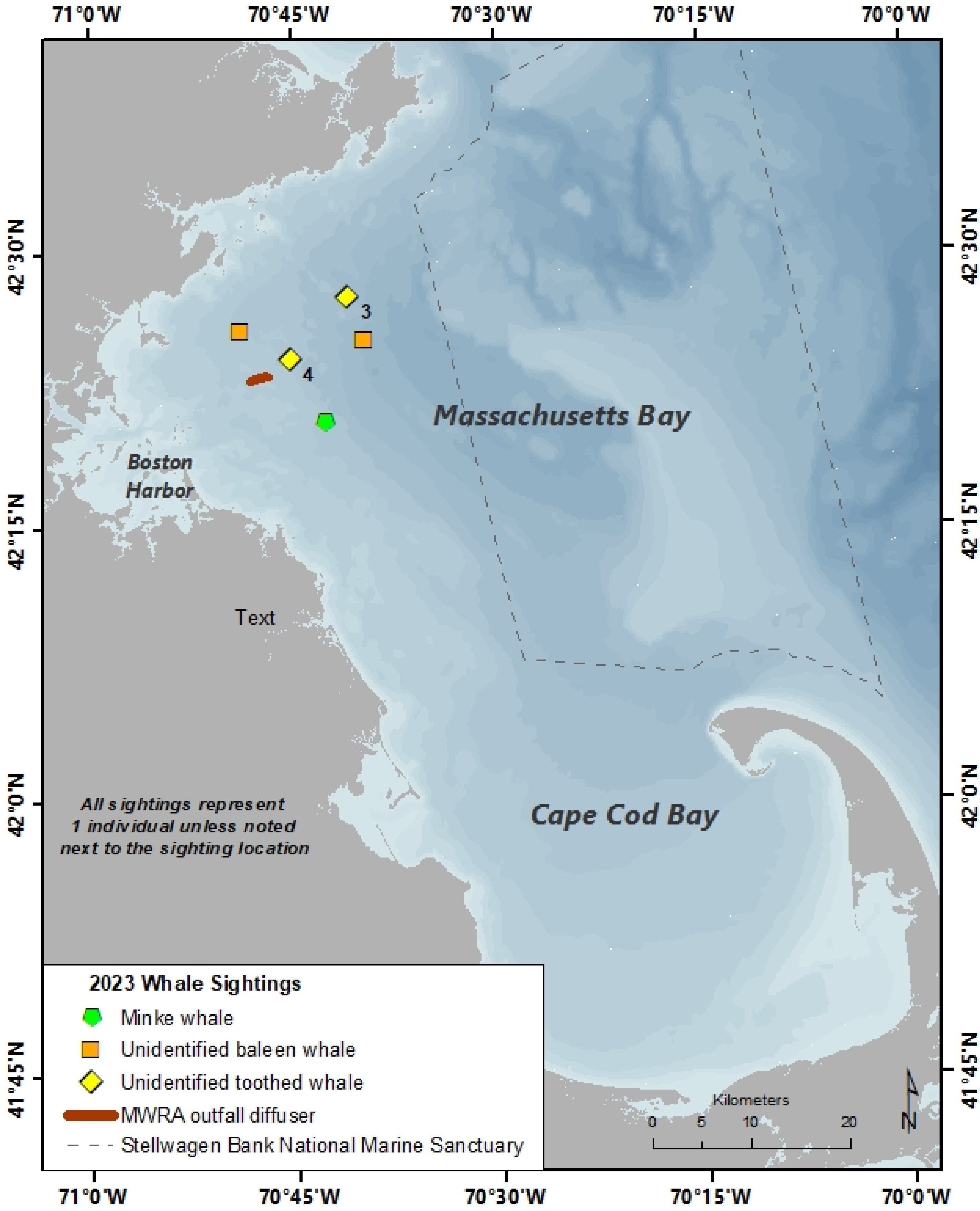


Figure 2-29. Locations and number of whale sightings and whale species sighted during the 2023 surveys.

3 ANALYSIS OF THE LONG-TERM MONITORING DATASET

3.1 2023 TRIPOS MUELLERI BLOOM AND LONG-TERM TRENDS

The highlight of 2023 was the major regional phytoplankton bloom of *Tripos muelleri* which resulted in extremely low nitrate levels, high chlorophyll and POC concentrations, and contributed to low bottom water DO throughout Massachusetts Bay. *Tripos* blooms have occurred around the world and were documented in the Gulf of Maine in the early 1900s (Bigelow 1924). In 1976, a large *Tripos muelleri* bloom occurred in the New York Bight that resulted in widespread anoxia and a $60 million loss to the shellfish industry along the New Jersey coast (Malone 1978; Mahoney 1978; Falkowski et al. 1980). The potential factors contributing to the 1976 bloom include warm winter water temperatures, large river inputs, few storms, a deep summer pycnocline, persistent winds from the south, inputs of carbon from offshore waters, and low grazing pressure by zooplankton (Falkowski et al. 1980).

In Massachusetts Bay, *Tripos muelleri* abundance typically reaches peak abundance of approximately 1,000 cells L^{-1} in late summer (**Figure 3-1**). This late summer bloom pattern is similar to that observed by Henry Bigelow and coworkers in Massachusetts Bay in the early 1900s (Bigelow, 1924). *Tripos muelleri* had a much different bloom timing in 2023 with elevated abundance early in the year, increasing sharply by April, reaching peak abundance in May or June and, most notably, reached abundance levels that were 13 to 20 times the long-term (1992-2022) mean levels previously observed in Massachusetts Bay (**Figure 3-1**). The extraordinary, monospecific *Tripos muelleri* bloom was regional, with phytoplankton monitoring programs noting elevated *Tripos* abundance from Maine to Rhode Island during spring/summer 2023. These simultaneous and synchronous patterns suggest that regional drivers (weather, climate, oceanographic variation) are important determinants of phytoplankton patterns regionally. Fortunately, unlike the 1976 bloom in the New York Bight, DO levels did not reach anoxic or even hypoxic levels in Massachusetts Bay in 2023.

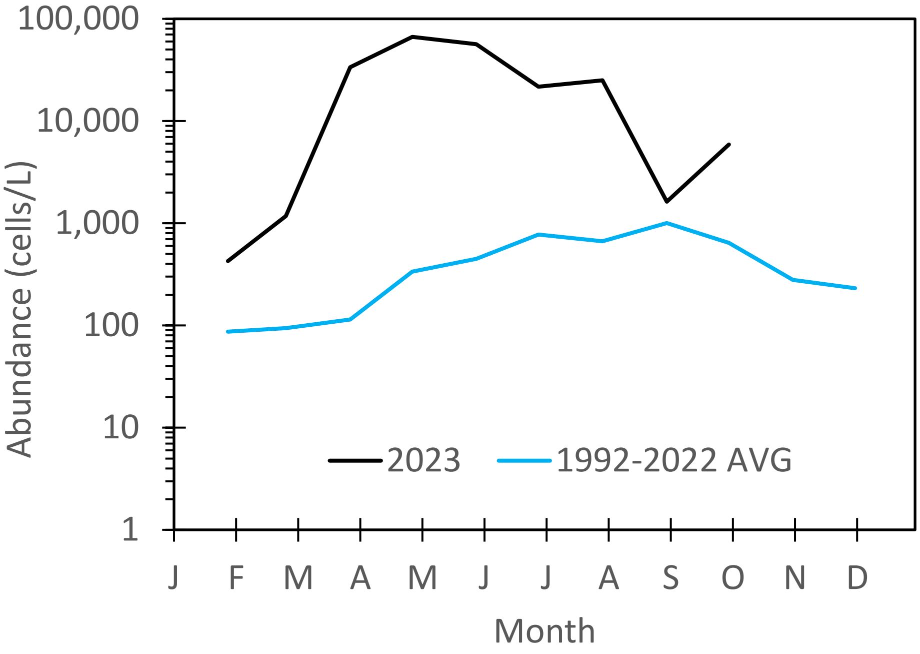
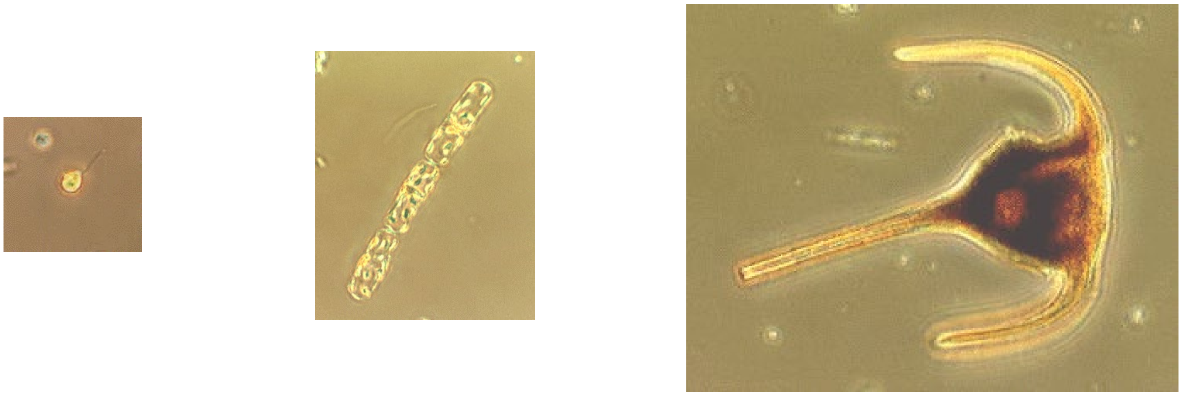


Figure 3-1. Average abundance of *Tripos muelleri* (cells L^{-1}) in 2023 compared to 1992-2022. Data averaged by depth and from stations F06, F13, F22, N04, and N18.

Tripos muelleri cells are motile and can swim 10-20 m per day (Smayda 2000). *Tripos* has an ecological strategy that uses this high motility to balance light acquisition and nutrient acquisition during stratified conditions. *Tripos* populations are generally found near the bottom of the pycnocline, often dominate sub-surface chlorophyll maximum flora, and use daily vertical migration to access light during the day and, by swimming downward, access more abundant nutrients near or below the pycnocline. However, *Tripos muelleri* is far larger than most other phytoplankton species (**Figure 3-2**) and have a relatively slow growth rate of 0.1 to 0.3 divisions per day (Smayda 2000). Microflagellates, which are the most abundant phytoplankton in Massachusetts Bay, are about three micrometers long and wide, while *Tripos muelleri* is at least 20 times wider, about 100 times longer, and contains about 1,000 times the amount of carbon in each cell. *Tripos* grows slower than other types of phytoplankton, although there is evidence that growth rates in the region were higher than usual during the spring of 2023, perhaps a response to warming waters. The March-April *Tripos* population growth rate has been increasing over the past 10 years (data not shown). Winter warming, altered rain and snow melt patterns, altered wind patterns, and earlier onset of persistent stratification contributed to the 2023 *Tripos* bloom which may be an expression of changing late winter conditions and phytoplankton succession in Massachusetts Bay.



Tripos muelleri
60-90 µm wide, 200-400 µm long
About 10,000 pg carbon/cell
Maximum 50,000 pg carbon/cell

Figure 3-2. Comparison of *Tripos muelleri* size and carbon content to other numerically dominant species observed in Massachusetts Bay. Photo credits David Borkman, Pausacaco Plankton, Saunderstown, Rhode Island.

To accumulate the *Tripos* abundance levels observed during 2023, prolonged periods of persistent stratification are required (Cushing 1989; Hunt et al. 2010). MWRA monitoring indicated that 2023 had the strongest and most persistent stratification observed during 1992-2023 (see **Figure 2-5**). Stratification of the water column in May is correlated with June *Tripos muelleri* abundance in Massachusetts Bay, because stable conditions are best for this slow-growing, motile species (**Figure 3-3**; Hunt et al. 2010). The early onset, persistent, and strong stratification observed during 2023 is the physical forcing that favored, and likely promoted, the extraordinary 2023 *Tripos muelleri* bloom throughout the Gulf of Maine.

Several lines of evidence suggest that seasonal phytoplankton succession patterns are in a state of flux in the Gulf of Maine (Staudinger et al. 2019), including Massachusetts Bay. Historically diatoms have dominated the winter-spring bloom in Massachusetts Bay. However, diatoms, particularly winter-spring diatoms like *Detonula confervacea* and *Thalassiosira nordenskioeldii*, have been in decline in

Massachusetts Bay (**Figure 2-22**) and regionally for the past 20 years. During this initial period of winter-spring diatom decline, a different phytoplankton functional group, the colonial prymnesiophyte *Phaeocystis pouchetii*, dominated the winter-spring phytoplankton (Borkman et al. 2016). In the past decade, *Phaeocystis* has also declined in abundance, leaving an 'open niche' for other phytoplankton functional groups. Similarly, *Alexandrium catenella* has shown a general decline in abundance in the western Gulf of Maine over the last decade or so, with only occasional higher concentration blooms in Massachusetts Bay in recent years. In contrast, blooms of this species have increased on Cape Cod within shallow estuaries and embayments.

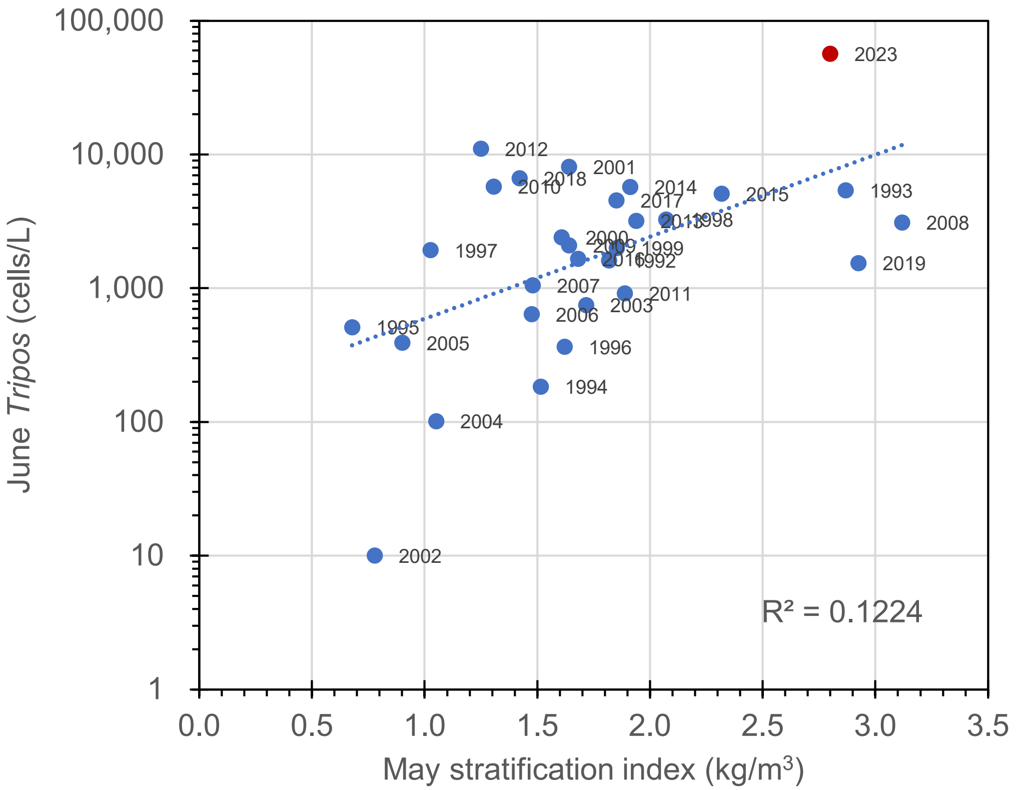


Figure 3-3. Stratification (kg m^{-3}) in May versus *Tripos* abundance (cells L^{-1}) in June for the nearfield during 1992-2023. Based on comparison presented by Hunt et al. 2010.

3.2 DISSOLVED OXYGEN TRENDS

As noted in Section 2.4, bottom water DO concentrations were low in Massachusetts Bay in 2023 and exceeded the Contingency Plan thresholds for DO concentration and percent saturation in the nearfield and Stellwagen Basin (**Table i** and **Figure 3-4**). At Stellwagen Basin station F22, bottom water DO percent saturation levels in July (62.7%) and September (63.4%) were below the warning level threshold (67.2%) and concentrations were below the caution level threshold (6.23 mg L^{-1}) in July (6.20 mg L^{-1}), September (6.08 mg L^{-1}), and October (6.22 mg L^{-1}). In the nearfield, the October bottom water DO concentration of 5.96 mg L^{-1} exceeded the warning level threshold of 6.05 mg L^{-1}. The bottom water DO depletion rate was only 0.008 mg L^{-1} d^{-1} which is the lowest rate observed over the monitoring program, but this is because the rate is calculated from June to October and by June 2023 bottom DO levels were already very low.

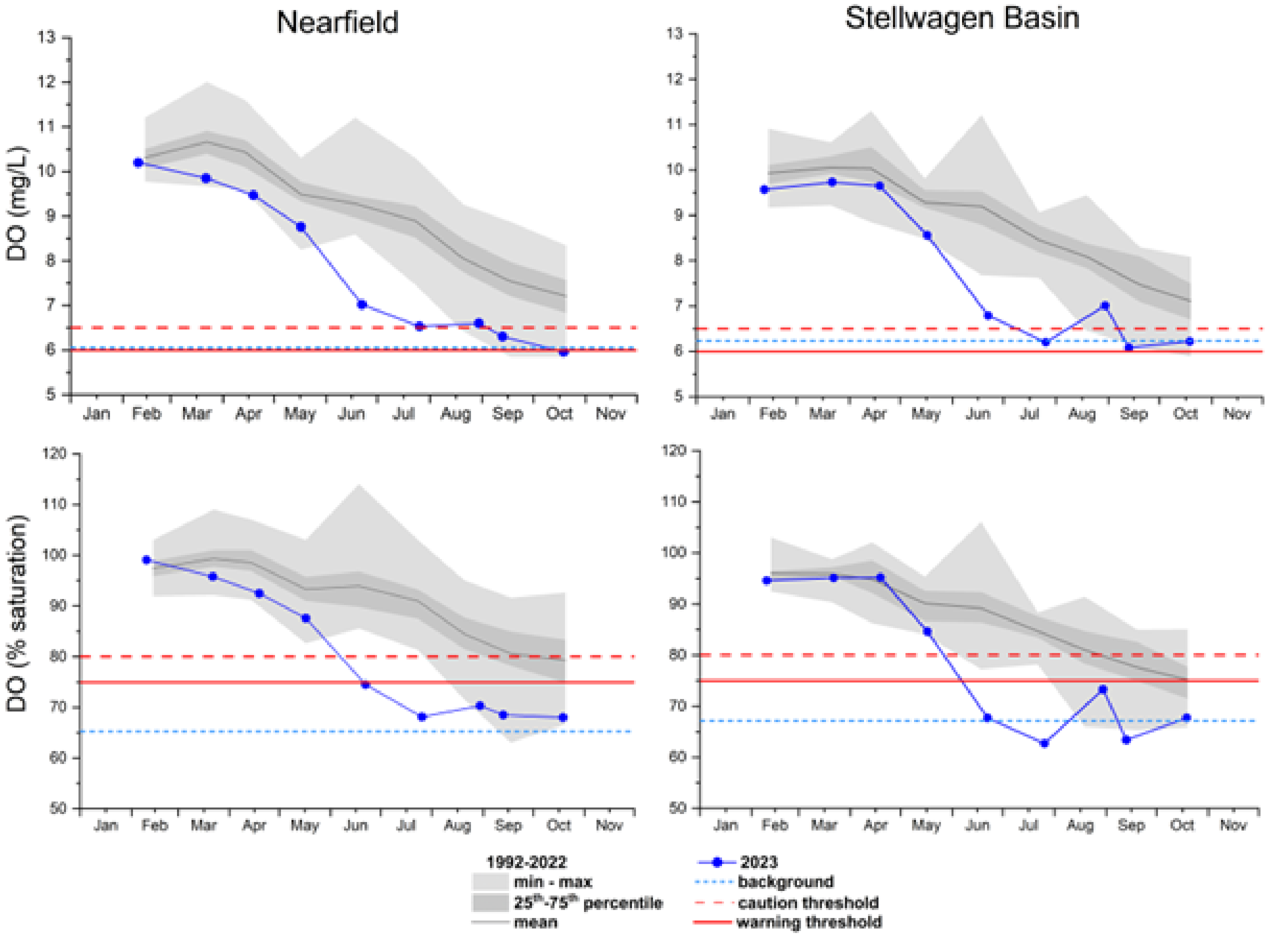


Figure 3-4. Survey bottom water dissolved oxygen concentration (mg L^{-1}) and percent saturation in the Nearfield and Stellwagen Basin versus Contingency Plan Thresholds for 2023 compared to prior years. 2023 results are in blue. Results from 1992–2022 are in gray: line is 50th percentile, dark shading spans 25th to 75th percentile, and light shading spans the range.

Early in the MWRA monitoring program, DO appeared to follow a pattern in which low DO in the deep waters of the nearfield was statistically associated with warm bottom waters and high salinity (Geyer et al. 2002). This observation was used to develop a regression model for bottom water DO based on water temperature and salinity (**Figure 3-5**). Historically, the model was relatively good at predicting bottom water DO, but over the past decade the model has tended to predict much lower concentrations than observed. For 2023, the model predicted much higher DO than was observed. The unusually low near-bottom salinity observed in 2023 would usually be associated with higher near-bottom DO, but the observed DO was approximately 1.5 mg L^{-1} lower than predicted by the model (**Figure 3-5**). This is a strong indication that some factor other than physical variability contributed to the unusually low DO levels in 2023.

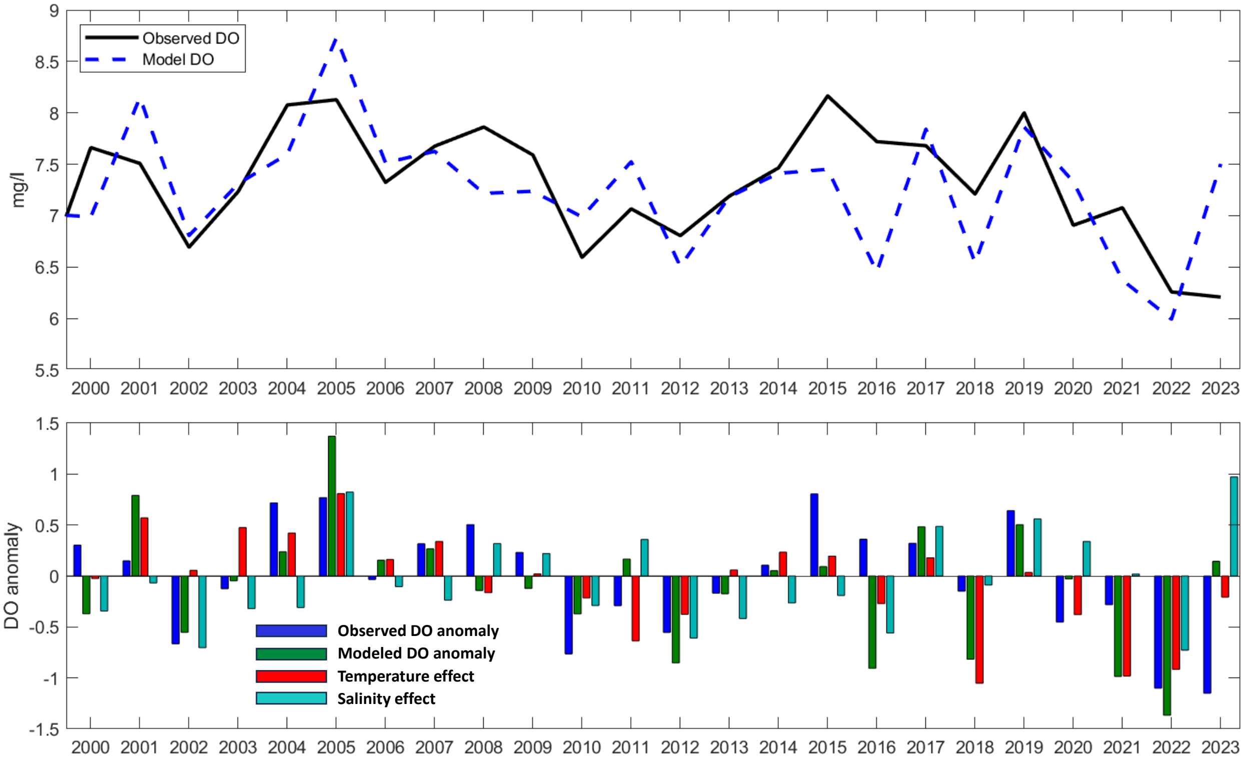


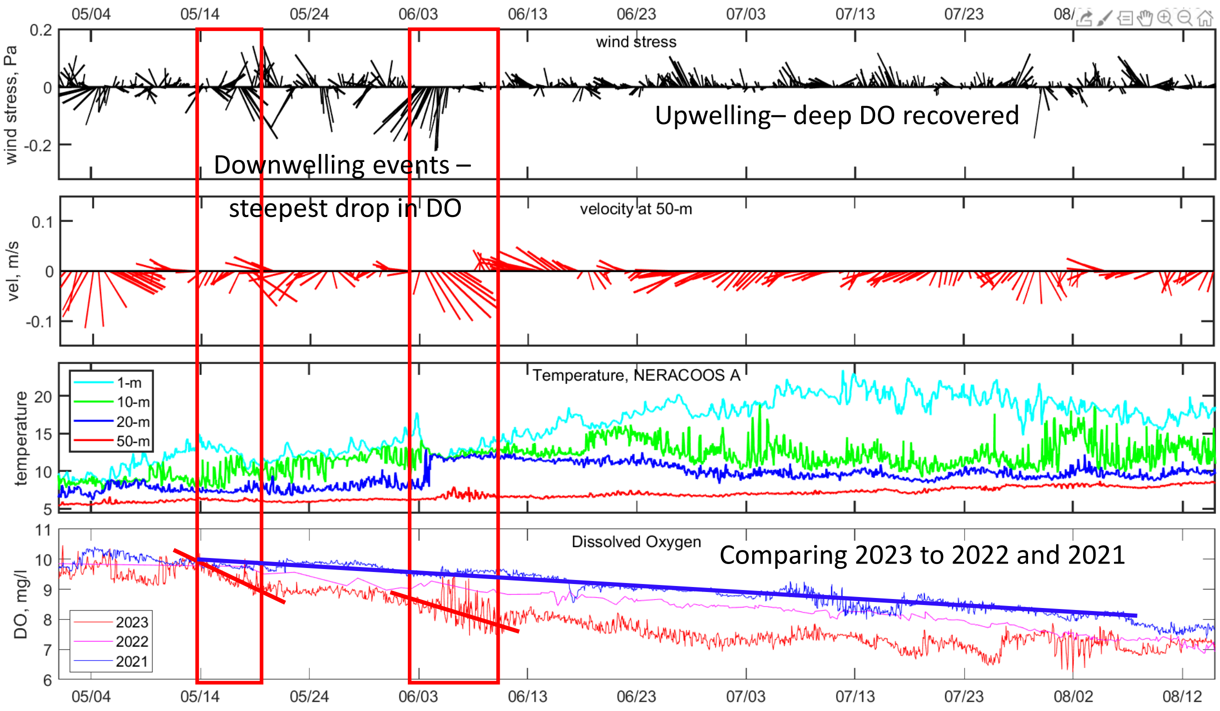
Figure 3-5. Average near-bottom dissolved oxygen in the nearfield during September-October, compared with linear regression model based on temperature and salinity variation (upper panel). Bar plot showing the individual contributions due to temperature and salinity for each of the years (lower panel).

A combination of factors played a role in the low levels of bottom water DO in 2023 – both physical (temperature and stratification) and biological (*Tripos* bloom). The impact of temperature on DO levels was evident from the start of the year with very warm water temperatures in February and March 2023 (see **Figure 2-3**), which led to low bottom water DO levels in February and even lower levels in March and April that were within the lower quartile of historic observations across Massachusetts and Cape Cod Bays. Freshwater inputs to the bay in April and May, along with the warmer surface water temperatures, resulted in an early onset of strong stratification in Massachusetts Bay (see **Figure 2-5**). These conditions contributed to the initiation, and likely promoted, the *Tripos muelleri* bloom in the bay and regionally and also shut off the already low DO bottom waters earlier than typically observed. Unsurprisingly, bottom

DO levels show a steep downward trend from April to July, reaching by far the lowest values observed during the monitoring period for both June and July (**Figure 3-4**). For the rest of the summer and early fall, the bottom water DO concentrations level out, possibly due to the influence of upwelling in August. Comparison of the nearfield decrease in DO to station F22 in Stellwagen Basin indicates that an anomalously steep decline in DO occurs in the farfield, somewhat earlier than the comparable decline in the nearfield. This suggests that this is a regional rather than local phenomenon.

NERACOOS observations during 2023 suggest that the DO dropped more steeply during downwelling events (**Figure 3-6**). The buoy data also highlight that the overall drop in bottom water DO levels between May and July 2023 showed a steeper decline than 2021 and 2022 data, suggesting that some factor other than the physical variability was causing the steep decline in DO. The rapid decrease and low bottom water DO levels were likely due to biological decomposition of senescent *Tripos* biomass and oxygen consumption in the bottom waters. Upwelling or mixing in July and August led to a leveling off of the decline, but bottom water DO concentrations continued to decline into September and/or October 2023.

The warmer water temperatures contributed to lower DO concentrations according to the regression model (**Figure 3-5**; bottom panel). However, 2023 was also a wet year overall, with high winter, summer and fall river flow which according to the regression model should have resulted in much higher bottom DO concentrations. The reason for the difference between model expectations and observation is the impact of the very high chlorophyll and POC concentrations from the *Tripos* bloom providing additional biomass to fuel decomposition and DO utilization in the bottom waters. Fortunately, July and August upwelling/mixing slowed the rate of decline and hypoxic conditions were not observed in the bays.



Downwelling events – steepest drop in DO

Upwelling– deep DO recovered

Comparing 2023 to 2022 and 2021

Figure 3-6. **NERACOOS A01 data for 2023.** Top panel - wind stress (Pa); second panel – wind speed (m s^{-1}) and direction; third panel – temperature (°C); and bottom panel – DO concentration (mg L^{-1}).

MWRA's long-term monitoring and studies by other agencies and scientists have documented increasing water temperatures in Massachusetts Bay and the broader Gulf of Maine (i.e., Pershing et al. 2015). Increased water temperatures can lead to lower DO concentrations, both locally and regionally. Within the MWRA monitoring area, increased water temperatures may be one factor leading to decreases in DO levels and subsequent Contingency Plan threshold exceedances in recent years.

In 2022, following two years of DO Contingency Plan exceedances, MWRA began an internal review of water temperature and DO concentrations over its 1992–2022 monitoring period (Codiga and Wu 2022). The analyses focused on eight stations across Massachusetts Bay using data from all five water depths sampled. The analyses showed clear and consistent increasing temperatures and declining DO concentrations across all stations and all water depths. Average April-October warming rates were about 0.4 to 0.6°C per decade. Dissolved oxygen concentrations declined about 0.17 to 0.23 mg L^{-1} per decade.

The long-term time series of summertime water temperature based on the NOAA NDBC buoy 44013 shows surface waters warming nearly 1 °C per decade (see **Figure 2-7** top). Similar increases have been observed at NERACOOS buoy A01, where mean surface water temperatures in July and August have also risen steadily about 0.6 to 0.8°C per decade for more than 20 years (data not shown). A review of the long-term wind data at the NDBC buoy indicates that the east-west wind stress shows an increase in the incidence of summertime winds coming from the southeast rather than the southwest (see **Figure 2-7** bottom). This trend may be influencing long-term warming, based on preliminary modeling by Malcolm Scully at WHOI. The changes in wind directions may result in decreased summertime upwelling as well as changes in the influx of water from offshore, both of which could contribute to warmer waters in the bay and subsequently lower DO levels.

4 SUMMARY

The most remarkable event in 2023 was the extraordinary phytoplankton bloom of *Tripos muelleri*. Notable seasonal patterns in physical oceanographic and water quality parameters were closely associated with the bloom from its initiation and growth to its senescence and decomposition. Warm winter/spring temperatures and wet conditions in April led to early onset of strong, seasonal stratification contributing to the initiation of the bloom. Extremely low nitrate levels and historically high chlorophyll and POC concentrations in May and June were due to the magnitude and duration of the bloom. The low bottom water DO concentrations observed in June and July throughout Massachusetts and Cape Cod Bays resulted from bloom senescence and decomposition. The *Tripos muelleri* bloom was regional, with phytoplankton monitoring programs noting elevated *Tripos* abundance from Maine to Rhode Island during spring/summer 2023. These simultaneous and synchronous patterns suggest that regional drivers (weather, climate, oceanographic variation) are important determinants of phytoplankton patterns regionally.

Air and surface water temperatures were warm in winter/spring 2023 and in combination with wet conditions in April led to an early onset of strong seasonal stratification. Merrimack River flow continued to be substantially higher than long-term levels for the rest of 2023 (**Figure 2-4**) contributing to persistent, strong stratification observed in Massachusetts Bay throughout the summer and fall (**Figure 2-5**). The persistence of stratified conditions from April to October was one of the factors contributing to low bottom water DO levels in 2023.

Nutrient concentrations in Massachusetts and Cape Cod Bays were generally consistent with typical seasonal patterns, with naturally elevated concentrations in winter/spring, decreases during the summer months and then increases in the fall (**Figure 2-8**). From March to April, there was a sharp decline in NO_3 concentrations throughout Massachusetts Bay during initiation of the *Tripos muelleri* bloom, reaching historic minima at deeper offshore stations (**Figure 2-9**). Nitrate concentrations remained exceptionally low from April through July with levels depleted at most stations. The bloom also produced historically high chlorophyll levels and POC concentrations were more than double historic maxima (**Figure 2-14** and **Figure 2-15**). The high May and June 2023 chlorophyll concentrations led to a nearfield summer seasonal mean nearly double the Contingency Plan caution level threshold and also resulted in an exceedance of the annual chlorophyll threshold (**Table i**). This is the first time since the bay outfall began discharging that chlorophyll thresholds were exceeded.

In 2023, bottom water DO concentrations were relatively low in winter due to warm water temperatures and decreased quickly with the early onset of strong, seasonal stratification in April and May (**Figure 2-18**). June and July levels were well below historic minima at many stations in 2023. The rapid decrease and low bottom water DO levels were due to the combination of strong stratification and biological decomposition of senescent *Tripos* biomass. Upwelling or mixing in August led to a leveling off of the decline, but bottom water DO concentrations continued to decrease into September and October. Lower DO values were also observed at stations in Cape Cod Bay with minima of <4 mg L^{-1} from July to September 2023 (**Figure 2-19**). Bottom water DO levels below long-term minima at many stations from June to October led to DO Contingency Plan threshold exceedances in both the nearfield and Stellwagen Basin (**Table i**).

Fortunately, unlike 2019 and 2020, there were no observations of hypoxic to anoxic conditions in shallow, nearshore Cape Cod Bay waters. Increased water temperatures and stratification resulting from regional changes in long-term summer wind patterns have been identified as a primary factor in the 2019 and 2020 hypoxic DO events in Cape Cod Bay (Scully et al. 2022). These factors continued to play a role in lower DO levels in 2023, but it was the additional biomass from the *Tripos muelleri* bloom supporting increased decomposition and oxygen consumption in the bottom waters that led to the historically low DO concentrations in 2023.

Annual total phytoplankton abundances measured in 2023 were close to long-term mean levels (**Figure 2-21**). Total phytoplankton abundance was dominated by elevated microflagellate and dinoflagellate abundance throughout the year especially during the major regional *Tripos muelleri* bloom April through August. *Alexandrium* abundances were very low in Massachusetts Bay in 2023 and well below the rapid response and contingency thresholds of 100 cells L^{-1}. PSP toxicity was undetectable in Massachusetts Bay, in the coastal waters from the New Hampshire border to Cape Ann, and throughout the Gulf of Maine (eastern and western) in 2023 except for a few embayments along the eastern side of Cape Cod. It is unclear why there was not an *Alexandrium* bloom in 2023 as the abundances in April, though low, were elevated versus historic levels (**Figure 2-25**). Physical oceanographic conditions were conducive for dinoflagellates in April and May 2023. It may be that the *Tripos* bloom limited *Alexandrium* growth through allelopathic mechanisms or nutrient limitation due to the extremely low NO_3 concentrations.

Zooplankton taxa, seasonal patterns, and abundances in 2023 were generally similar to those seen in previous years (**Figure 2-26**). Total zooplankton abundance was high in June and July, due primarily to increases in bivalve veliger larvae. There were also high abundances of meroplankton in October, which was dominated by radiolarians. Radiolarians had not been observed prior to 2020 but have now appeared for four years in a row. Radiolarians are more oceanic and warmer water taxa than those typically observed in the MWRA sampling area. Summertime surface water temperatures are warming at a rate of nearly 1 °C per decade (**Figure 2-7**). The warmer temperatures may be due a range of influences including summertime winds shifting and weakening upwelling (Scully et al. 2022) and more regional warming of the Gulf of Maine associated with the northward extension of the Gulf Stream (Townsend et al 2023; Goncalves Neto et al. 2021). The warming waters may be influencing changes in the species distribution and abundance in Massachusetts Bay and are important to consider when evaluating trends in many Massachusetts Bay monitoring parameters going forward.

As typically observed, the extent of the bay outfall effluent plume was characterized by elevated NH_4 concentrations. The 2023 NH_4 concentrations were similar to those observed post-diversion compared to the baseline period before operation of the outfall in the bay, where they were lower in Boston Harbor, higher and variable in the nearfield and vicinity, and generally unchanged in the rest of Massachusetts and Cape Cod Bays (**Figure 2-10**). The survey-to-survey variability in high concentrations observed at stations nearest the outfall is due to the location of the effluent plume during sampling and where the samples are collected along the mixing zones associated with the plume. Elevated NH_4 concentrations were also observed below the pycnocline south of the bay outfall at station F15 from June to July (Figure 2-13). These higher NH_4 levels are likely due to a combination of both the effluent plume and degradation of the *Tripos* bloom as the cells die off and decompose below the pycnocline. Ammonium concentrations at Boston Harbor station F23 in 2023, as in other post-discharge years, were much lower than during the years when wastewater was discharged directly to the harbor. These patterns are consistent with pre-diversion model simulations (Signell et al. 1996). Spatial patterns in NH_4 concentrations in the harbor, nearfield, and bays since the diversion in September 2000 have consistently confirmed the model predictions (Taylor 2016; Libby et al. 2007).

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